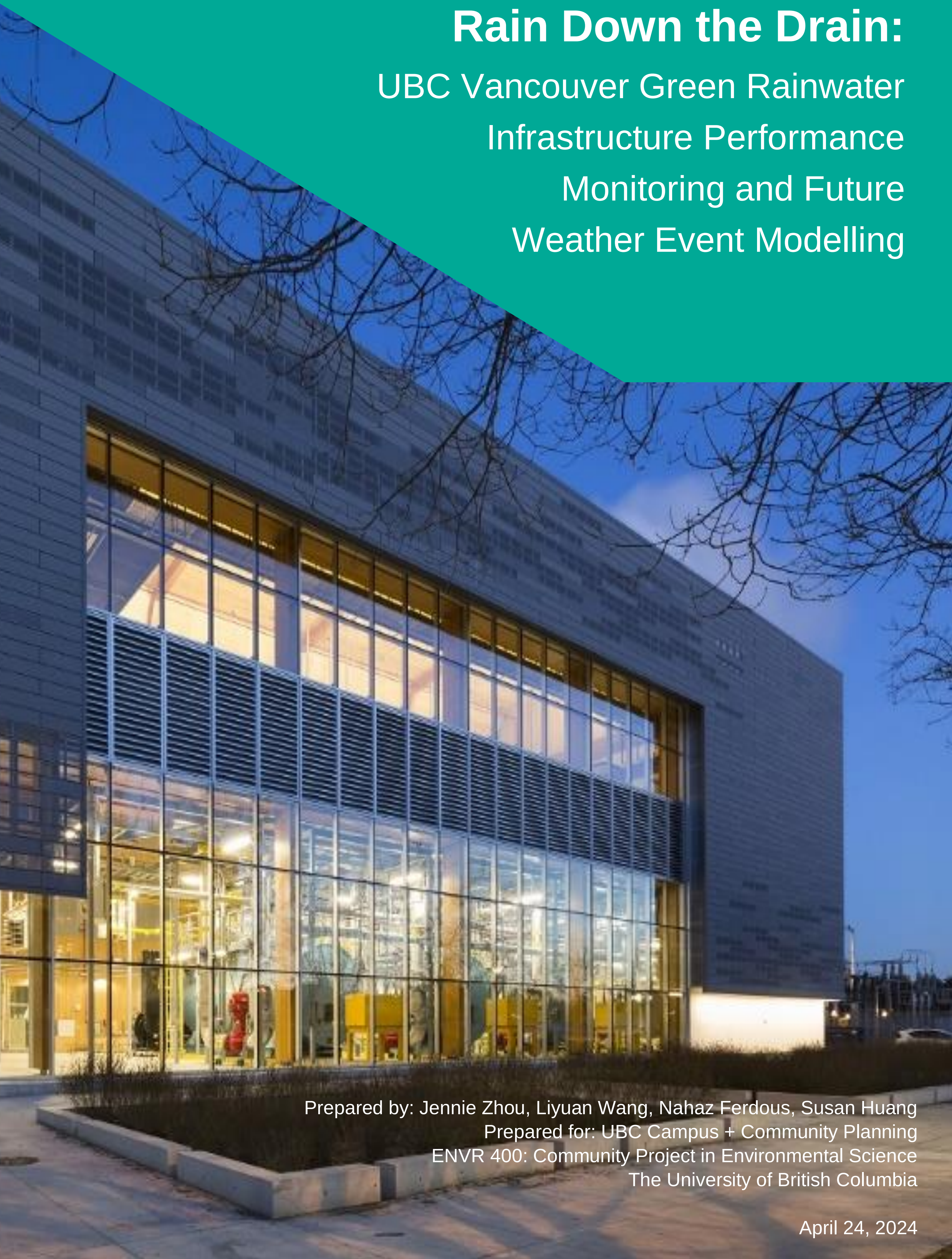
Rain Down the Drain:

UBC Vancouver Green Rainwater Infrastructure Performance Monitoring and Future Weather Event Modelling



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Cover Photo: Ema Peter

SEEDS Sustainability Program

Executive Summary

Green rainwater infrastructure (GRI) plays an important role in urban stormwater management by mimicking natural hydrological processes and reducing the adverse impacts of runoff on the environment. GRI includes various infrastructure such as green roofs, rain gardens, permeable pavements, tree plantings, and constructed wetlands. GRIs can bring multiple benefits to urban areas. It helps manage stormwater, prevent flooding and erosion, and improve water quality through natural filtration. Furthermore, it could reduce urban heat island effects, enhance air quality, and support biodiversity by providing habitat for various species. Additionally, the implementation of GRIs could yield multiple collateral advantages such as the enhancement of visual appeal and the facilitation of recreational, social, and public spaces.

As anthropogenic climate change impacts and environmental degradation due to urban expansion continue to intensify, the hydrological systems of the University of British Columbia's (UBC) Vancouver campus will face increasingly significant challenges over time. In the face of these challenges, understanding the performance of existing GRIs on campus is crucial to achieving and planning for effective stormwater management at UBC. To investigate the performance of existing GRIs on campus, this project assessed the effectiveness of the Campus Energy Centre (CEC) rain gardens (RGs) by evaluating their capacity for peak flow reduction during precipitation events between January and February 2024. Based on the outcomes, site-specific recommendations to enhance performance and build resilience were made, along with more general recommendations that are widely applicable across campus.

Three objectives were identified to evaluate the effectiveness of the GRI and to make recommendations:

1. How did the CEC RGs perform, in terms of peak flow reduction, during rainfall events between January 2024 to February 2024?
2. To what extent were the CEC RGs expected to mitigate flooding posed by climate-adjusted rainfall projections under storm event scenarios with a frequency of 2-year, 10-year, and 100-year return periods and varying storm durations of 5 minutes to 24 hours?
3. What practices can be employed on the CEC RGs to improve their overall ability to manage projected future extreme weather events, based on existing literature around GRI maintenance guidelines?

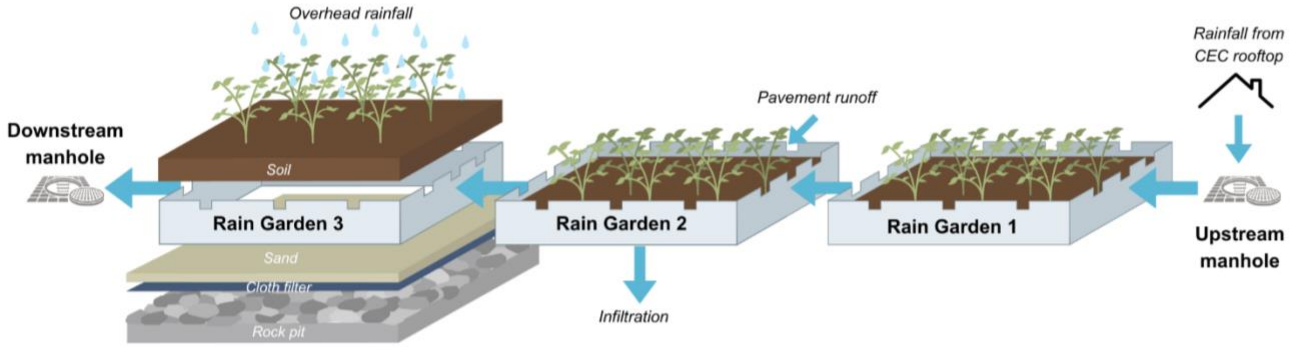

Figure 1. Simplified illustration of the study site's system of three RGs. Blue arrows represent the flow of water. After passing through the downstream manhole, water is then directed to a detention tank and drained into existing storm sewer infrastructure as part of the North Catchment, which eventually discharges into the ocean.

To meet the stated objectives, the project was organized into three distinct phases. Firstly, the peak flow reduction of the CEC RGs was investigated by monitoring the difference between total inflow and outflow, which reflected the site's water infiltration and storage capacities. To track the flow of water through the RGs, HOBO U20 water level loggers were installed in manholes upstream and downstream of the system, and, within the curbside 'inlets' of the RGs to measure the inflow of rainwater from surrounding pavements and the roof of the CEC building (Fig. 1). Data collection occurred between January 28 to February 20, 2024, and results showed that the system effectively managed stormwater inflows without reaching capacity limits.

To test the study sites' ability to withstand increased projections of precipitation, the system of RGs was modelled using the United States Environmental Protection Agency's Storm Water Management Model (SWMM) 5.2 software, where designed storm events for various return periods and durations were ran through the model to forecast its future performance in 25 to 50 years. Similar to trends observed from the field data collection, the RGs were found to effectively manage stormwater which entered the system by reducing peak flow. However, separate from the effectiveness of the rain gardens, runoff from the surrounding pavement still occurred in all the model scenarios which indicated that a portion of the rainfall impacting the pavements did not enter the rain garden system.

The final phase of the project involved developing recommendations to enhance the garden's functionality, including systematic debris removal to prevent blockages, a strategic approach to fertilization and low-phosphorus products, and advocating for the use of water and environmentally safe cleaning agents in line with UBC's sustainability targets.

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Glossary

- Campus Energy Centre (CEC): The building integrated into the rain garden system via the rooftop rainwater entering the rain garden system.
- Climate Resilience: The capacity of a system to withstand and recover from the impacts of climate change, including extreme weather events and long-term shifts in weather patterns.
- ESB Weather Data: Meteorological data collected by instruments located on the rooftop of the Earth Sciences Building (ESB) at the University of British Columbia, used for monitoring and researching local weather conditions.
- Green rainwater infrastructure (GRI): Infrastructure designed to manage stormwater runoff using natural processes, such as vegetation and permeable surfaces, to mimic natural hydrological systems.
- Hydrological System: The system of water circulation on Earth, including processes such as precipitation, evaporation, and runoff.
- Low Impact Development (LID): An urban planning and design approach aimed at managing stormwater runoff to mimic natural hydrology and minimize environmental impacts.
- Peak Flow Reduction: The reduction in the maximum flow rate of stormwater runoff, typically achieved through the use of stormwater management practices.
- Rain Garden (RG): A landscaped area that uses natural processes to collect, absorb, and clean stormwater runoff. The RGs in the study site were labelled as RG #, where the number in place of # corresponds to each RG's proximity to the upstream manhole. RG 1 was the closest while RG 3 is the farthest.
- Rainfall Events: Periods of rainfall or snowfall, usually measured over a specific time interval.
- Return Period: A statistical measure representing the average interval between events of a certain magnitude, often used in hydrology to estimate the frequency of extreme weather events.
- Storm Water Management Model (SWMM): A computer program developed by the US Environmental Protection Agency (EPA) for simulating stormwater runoff and drainage systems in urban areas.
- University of British Columbia (UBC): A major public university located in Vancouver, Canada.

Background

Green Rainwater Infrastructure, and its Context Within UBC

As urban landscapes continue to evolve, urbanization and climate change impacts are two processes that occur simultaneously. Current and future landscape designs must be able to address the needs of urban development whilst also building infrastructure that promote sustainability and safety in the face of potentially worsening climates.

Green rainwater infrastructures (GRIs) were low-impact development (LID) practices such as permeable pavements and rain gardens (RGs), which aimed to enhance post-development hydrology so that it mimics pre-development hydrological conditions (Davis et al., 2009). As summarized in the literature review conducted by Chui et al. (2017), GRI could cleanse stormwater and reduce its runoff quantity whilst providing environmental value by increasing biodiversity, moderating local microclimates, and sequestering carbon.

As the University of British Columbia (UBC) continues to evolve as an academic institution and urban space, GRIs are increasingly becoming an important component to the campus environment. In collaboration with the SEEDS (Social Ecological Economic Development Studies) Sustainability Program and Campus + Community Planning, this research project utilized UBC's Campus as a Living Laboratory approach to assess an existing GRI site using field-collected data and performance modelling under different rainfall scenarios.

UBC's Hydrogeological Conditions and Development Plans

UBC's Vancouver campus is located on the traditional, ancestral, and unceded territory of the xʷməθkʷəy̓əm (Musqueam) First Nation; on the western edge of the Point Grey Peninsula, bounded by sea cliffs of the Pacific Ocean and the Pacific Spirit Park. According to a 2002 Hydrogeological and Geotechnical Assessment of UBC campus conducted by Piteau Associates, the peninsula predominantly had a layer of moderately permeable surface soil which overlies a moderately impervious till. As a result, swamps and poorly drained soils arose from UBC's groundwater system since water which soaked into the ground ended up perched above the till surface. As of 2002, the report found that around 9.6% of the average annual precipitation seeped into the ground at a rate of approximately 3.9 $L/s/km^2$.

As outlined in the Campus Vision 2050 plan, UBC has extensive development goals for its Vancouver campus over the next three decades. Namely, the University is aiming for an additional 8.1 million sq. ft. of residential development along with 4.1 million sq. ft. of additional academic space. Furthermore, the expansion of the Millennium Line would bring two new SkyTrain stations to campus.

Urban developments reduced the potential for water infiltration near roads, parking lots, and buildings as impervious surface cover increases (McGrane, 2016). Moreover, a 2021 paper by Zhao et al. suggested that urban expansion changes urban micrometeorology, resulting in the urban heat island effect and the rain island effect, whereby the magnitude and frequency of extreme rainfall events increases in urbanized regions. With these compounded effects, the University must strive for infrastructure that minimizes the adverse impacts of urban development on the campus' ability to manage stormwater.

The 2017 Integrated Stormwater Management Plan (ISMP) stated that UBC is specifically looking at rainwater and cliff erosion management strategies such as an expanded use of GRIs across campus. GRIs were a form of nature-based solutions (NbS), which use natural or modified ecosystems to offer environmental, economic, and social benefits whilst increasing resilience (Luedke, 2019). Not only are NbS such as GRIs "strongly supported by the University," Eronen et al. (2021) found that UBC campus residents highly valued the aesthetics and visual appeal of stormwater management solutions, and thus, NbS were more favorably perceived by community members as well.

Future Climate Impacts and the Need to Implement GRIs

The potential of LIDs on UBC campus was explored by Birch (2023) using the United States Environmental Protection Agency's (US EPA) Storm Water Management Model (SWMM). The model results suggested that bioretention cells (such as RGs and bioswales) could accomplish both infiltration and flow reduction to improve storm resilience on campus. However, as these were results generated from a computer model, there was a need to investigate the actual effectiveness of existing GRI on campus as well as a need to explore GRI performance on a more local scale in terms of both modelling and field experiments.

The need for performance monitoring of GRIs at UBC was compounded by the possibility of climate change impacting future precipitation patterns in the region. According to climate modelling by Chhetri et al. (2019), Vancouver's precipitation is predicted to steadily increase during the wet season of October to March up through the 2080s, more weeks with extreme rain (>90th percentile) are also expected within the same timeframe. As seen during the 2021 British Columbia (BC) floods, infrastructure with inadequate climate adaptations could result in severe financial and structural damages as well as fatal human consequences (Hunter, 2021). A study by Gillet and colleagues (2022) estimated that human-induced climate change has increased the probability of extreme rainfall events in BC, such as those caused by atmospheric rivers by 120-133% within the October to December range. These future projections suggest that UBC must couple their ambitious development plans with climate adaptation strategies to reduce the negative effects of urbanized developments on campus' capacity to handle extreme rainfall events and prepare for the adverse impacts of climate change.

Project Study Site: UBC Campus Energy Centre Rain Gardens

The study site of this research project was the UBC Campus Energy Centre (CEC), which has a system of three RGs, connected by a perforated pipe, to manage stormwater on site before it enters campus' larger stormwater system.

Figure 2. Picture of the UBC Campus Energy Centre, showcasing all three rain gardens on the sidewalk (Photo by Ema Peter).

The site is located within UBC's North Catchment, which is drained by a spiral drain located adjacent to the Museum of Anthropology. The spiral drain outlet is at the mouth of English Bay, where discharge from the drain directly enters the ocean. The area near the drain is also where the largest erosion events on campus occurred over the past 75 years. In addition, the theoretical limit of the campus discharge rate under a 100-year storm is higher than the observed and calculated limits of the spiral drain, raising further concerns surrounding campus' capacity to handle extreme rainfall events (UBC Campus + Community Planning, 2017).

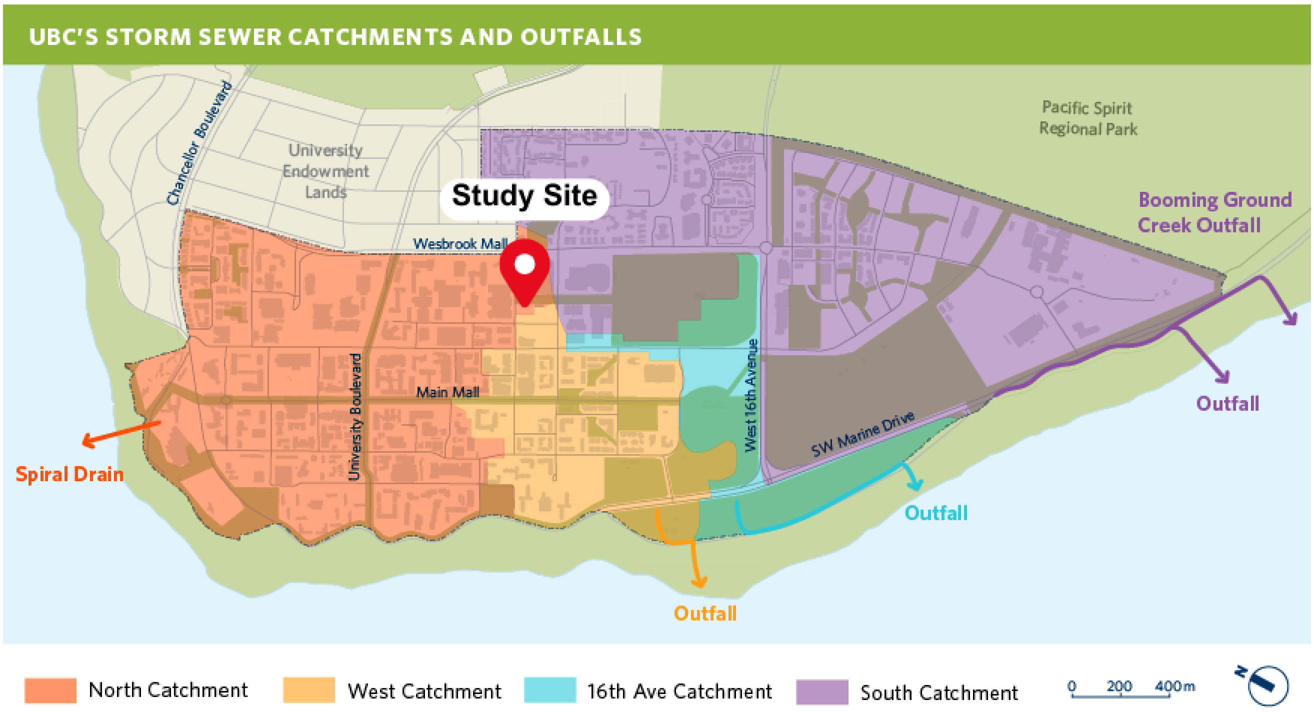

Figure 3. Map of UBC's Storm Sewer Catchments and Outfalls, with the study site indicated by a red marker (UBC Facilities: Energy & Water Services, 2017).

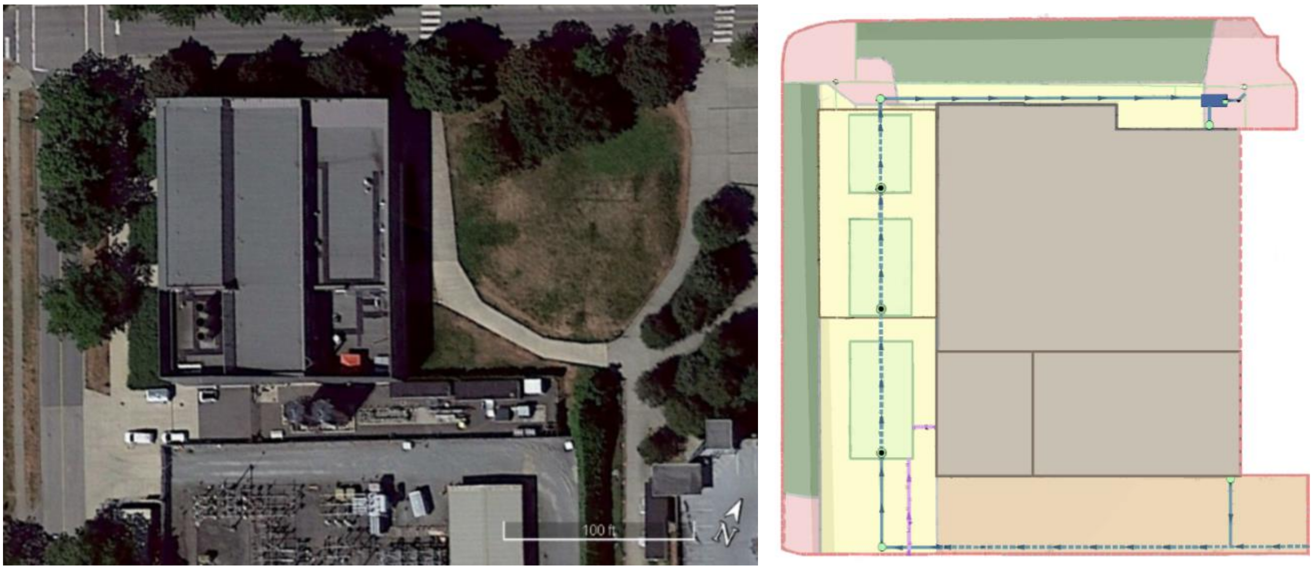

Figure 4. Side-by-side comparison between an aerial view of the study site from Google Earth (taken on July 29th, 2022) and the layout of the site as illustrated in the engineering drawings of the Nutrient Management Plan (UBC District Energy Centre, 2015).

Rain gardens were engineered landscapes designed to infiltrate and filter stormwater runoff and typically include layers of rock, soil, and native and/or adaptive vegetation that was resilient to extreme rain and drought events (Spraackman et al., 2022). According to the Nutrient Management Plan (2015), the CEC RGs were planted with *Salix purpurea* 'Nana' shrubs (also known as the Dwarf Arctic Willow), which thrives in moist, poor, or even intermittently flooded soils and is good for erosion control (Missouri Botanical Garden, n.d.).

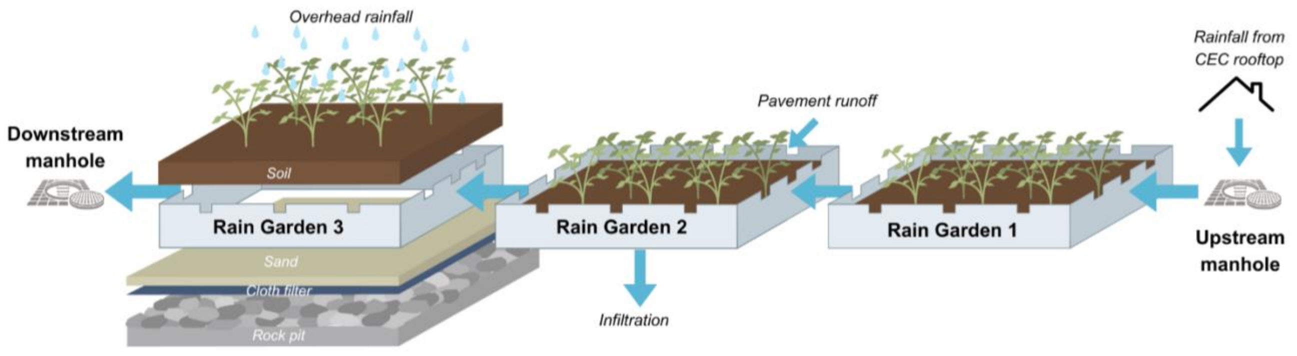

Figure 5. Simplified illustration of the study site's system of three RGs. Blue arrows represent the flow of water. After passing through the downstream manhole, water is then directed to a detention tank and drained into existing storm sewer infrastructure as part of the North Catchment, which eventually discharges into the ocean.

Project Purpose and Objectives

This research project provides a comprehensive analysis of the CEC RGs with respect to its performance as a stormwater management GRI, by answering the following questions:

1. How did the CEC RGs perform, in terms of peak flow reduction, during rainfall events between January 2024 to February 2024?
2. To what extent are the CEC RGs expected to mitigate flooding posed by climate-adjusted rainfall projections under storm event scenarios with a frequency of 2-year, 10-year, or 100-year return periods and varying storm durations ranging from 5 minutes to 24 hours?
3. What practices can be employed on the CEC RGs to improve their overall ability to manage projected future extreme weather events, based on existing literature around GRI maintenance guidelines?

Research Methodology

Research was conducted primarily through field data collection, qualitative assessment, and modelling of the study site. Field data collection included measuring the flow by unit conversion from measured pressure of rainwater both upstream and downstream of the RG system, as well as the runoff from the surrounding pavements feeding into the RGs. Qualitative assessment of the site was conducted through visual assessments relative to rainfall events, according to the criteria in Table 2. Finally, the CEC RG system was modelled with projected future rainfall events based on local, historical precipitation data. Literature research was conducted to supply recommendations for the site based on the visual assessments. Additionally, data from a weather station on the rooftop of the Earth Sciences Building (ESB) was provided courtesy of Dr. Roland Stull and UBC Weather Forecast Research Team (WFRT). Rainfall data and atmospheric pressure data from this weather station were utilized in this study.

Performance Monitoring

Field Data Collection Overview

This study aimed to assess the performance of the CEC RGs in terms of peak flow reduction during rainfall events from January to February 2024. The primary field data comprised of pressure measurements from inlets in the RGs as well as manholes upstream and downstream of the RG. These pressure measurements were converted into water levels (in meters) and subsequently translated into flow rates (L/s) and volumes (L) to evaluate the effectiveness of the RGs. In addition, the field data collection includes RGs visual observation, including whether there was garbage in RGs, debris near the inlets and ponding on the surrounding pavements.

The HOBO U20 was a pressure transducer, or water level data logger. 4 loggers were deployed at various locations in the GRI system: one at the upstream manhole, one at the downstream manhole, one at an inlet of RG 1, and one at an inlet of RG 2 as shown in Fig. 6 and Fig. 7. These inlets were chosen in effort to capture as much difference and diversity of observations, considering the orientation, accessibility, and estimated maximum and minimum flow rate from the respective inlets. The loggers were deployed to record data with a sampling interval of 5 minutes.

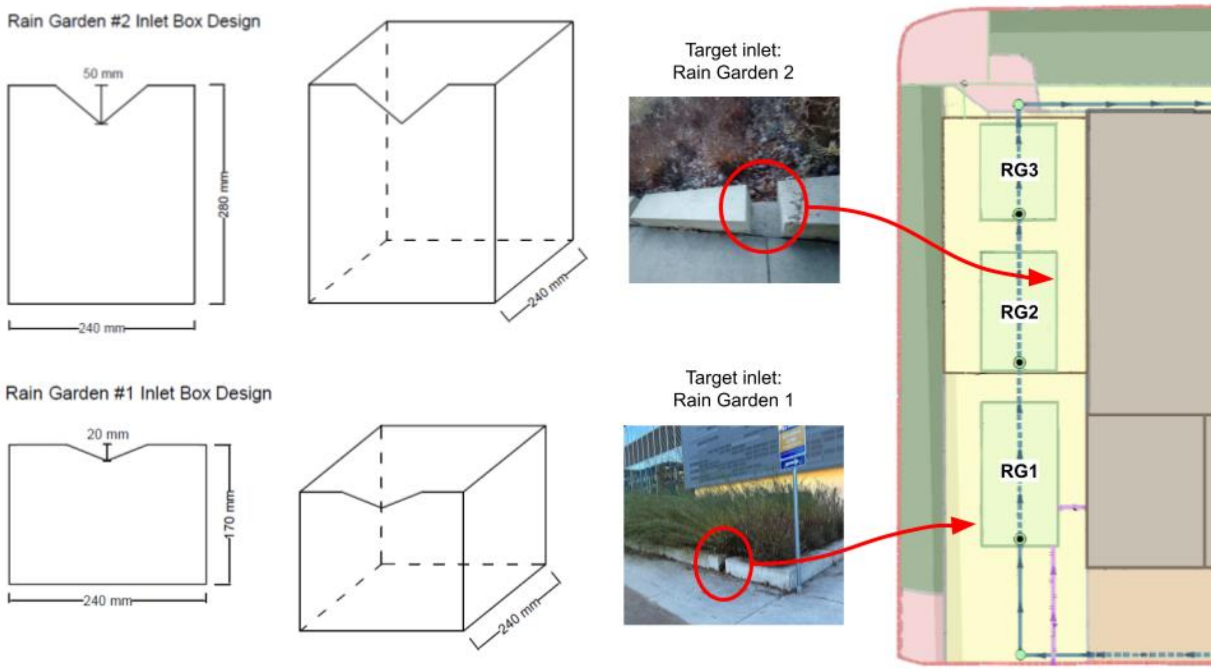

Figure 6. Weir box design with dimensions for both RG 1 & 2.

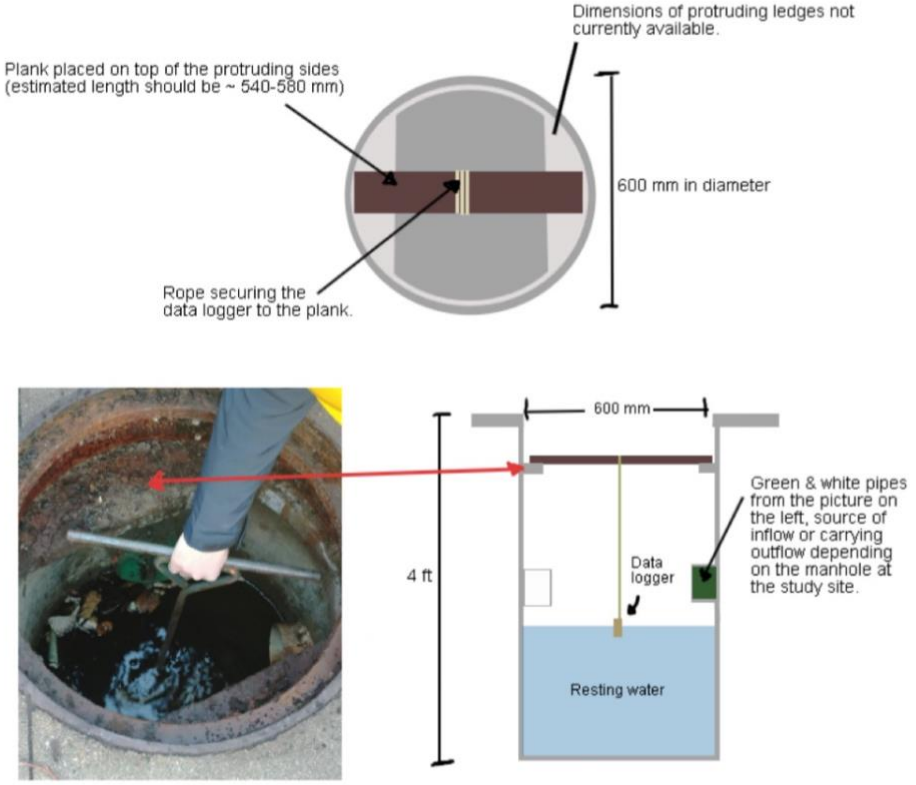

Figure 7. Measurement for the diameter of manhole and planks set up for hanging the water level loggers. Manhole inflow and outflow had the same size of the hole.

Data Processing and Analysis

The HOBO U20 loggers record pressure measurements that are influenced by changes in water level and atmospheric pressure. To isolate the pressure changes due to changes in water level, fluctuations in atmospheric pressure were removed using data provided courtesy of the WFRT. However, since the ESB rooftop was at a higher elevation (116m above ground level) compared to the RGs (20m above ground level), the standard pressures of the two elevations were calculated using the following formula from The Engineering Toolbox (2003): $101325 \times (1 - 2.557 \times 10^{-5} \times elevation^{5.2558}) \div 1000$. The adjusted atmospheric pressure was then calculated by subtracting the standard pressure of the rooftop from that of the RGs to obtain the hydrostatic pressure. This pressure was then converted from pressure in kilopascal (kPa) to decibars (dbar), from which water level was obtained as 1 dbar is equivalent to one meter of water depth. Water volume was calculated by multiplying the water depth by the area of the weir boxes and manholes respectively, as seen in the weir box designs and manhole illustration (Fig. 6 and 7). Additionally, as the ESB weather station data had sampling intervals of 15 minutes, the atmospheric pressure data was interpolated to match the 5-minute interval data from the water level loggers.

The total inflow travelling through the site system was calculated as the sum of the manhole inflow, the rain directly falling over the RGs and CEC building rooftop, and the total water flow from inlets into the RGs (total Inflow = inflow from the upstream manhole + direct rainfall over RG area + direct rainfall over CEC rooftop area + total inlet inflow). The initial inflow measurement at the upstream manhole also captured water flow from the nearby pavement. Outflow from the system obtained from the downstream manhole. It was assumed that rainfall at the study site was consistent with measurements from the ESB Weather Station. The areas of RG 1 & 2 & 3 were 94.280 m^2, 57.113 m^2, and 59.141 m^2, respectively. To calculate the lateral inflow from the surrounding pavements, two inlets across the three RGs were selected for data collection as shown in Fig. 6, and the total inlet inflow was calculated by averaging the observations from these two inlets and multiplying the average by the total number of inlets (36) across all RGs. All flow rates were calculated as volume change per 5-minutes divided by 300 seconds to obtain values in L/s. During data processing, all negative values of inflow were replaced with zero, to account for presumed water level fluctuations in the upstream manhole itself which were not representative of the flow rates of the system.

The inflow and outflow volumes were then used to calculate the peak flow reduction to evaluated site performance. Hourly precipitation (mm/h) from the ESB weather station was used to classify each rainfall event by the categories given in Table 1. Cumulative rainfall was calculated as the sum of all hourly precipitation measurements over the span of a rainfall event, divided by 4 to account for the 15-minute interval of data observations. Afterwards, peak flow reduction for each category of storm events was calculated as follows: (Maximum Total Inflow - Maximum Total Outflow) ÷ Maximum Total Inflow.

Table 1. Rainfall events were categorized following the criteria in the City of Vancouver report (Spraakman et al., 2022): a rainfall event was defined as having a minimum cumulative rainfall of 2.0 mm with a minimum 6-hour antecedent dry period. Events were categorized into three types based on total precipitation: Normal (≤ 24 mm), Large (> 24 mm and ≤ 48 mm), and Extreme (> 48 mm).

Cumulative Rainfall (mm)	≤ 24	> 24 ≤ 48	>48
Rainfall Event Category	Normal	Large	Extreme

Visual Assessment Criteria

To generate recommendations that are both appropriate for the site and best for present and future maintenance, research was conducted by reviewing existing scientific literature, GRI maintenance guides, and performing site-specific visual assessments during the data collection period.

The visual assessment was conducted according to the criteria in Table 2, adapted from Spraakman et al. (2022) and the Toronto and Region Conservation Authority report (2016). During the observational period (January 25 - February 20), project members documented the amount of debris, garbage accumulation, and the frequency of maintenance, without interfering with site conditions. Photos of the top and side views of each inlet were recorded with the listed standards, examples of which are shown in Fig. 8:

- **Top view:** Centering the inlet, showing a portion of pavement and RG.
- **Side view:** Horizontal, showing pavement and centering inlet.

Table 2. Visual assessment criteria. Criteria with an asterisk (*) follow the visual guide from the Toronto and Region Conservation Authority report (2016).

Visual Assessment	Criteria	Frequency of Assessment	Recording method
Ponding	Still water present in ponding area (around the inlets and on the sidewalk) 12 or 24 h after a rainfall event	12h after heavy rainfall events. 24h after heavy rainfall events.	Note in data collection sheet (see appendix B) if absent, photos of site if ponding present. Photo Rename Criteria and example: “RG1_I1_0120_T” would be RG1, inlet 1, Jan 20, Top view

Debris Accumulation	Any obstruction of water flows into the RG (note as concern if more than 33%). Ponding in front of the inlet present. *	During a rainfall event.	Note if visually significant flow difference compared to an adjacent inlet clear of debris.
Garbage Accumulation	Presence of garbage and trash in the RGs or around the inlets.	Per site visit.	Top and side view photos.

Figure 8. Photo requirements for visual observation record. Side view is shown on the left side. Top view is shown on the right side.

Modelling Future Projections

To address potential changes in future precipitation due to climate change, the CEC RG system was modelled in the US EPA's SWMM modelling software (Version 5.2) and subjected to storm events based on climate projections from a high emissions scenario (RCP8.5; SSP5-8.5). The resulting output was then used to evaluate the modelled RG system in terms of peak flow reduction, as well as supporting metrics such as the runoff coefficient (ratio of total precipitation entering the system to total pavement runoff).

SWMM Model Setup

As illustrated in Fig. 9, the RG system was composed of three rain gardens positioned next to the CEC building, with two manholes situated directly upstream and downstream of the gardens. In the model (Fig. 9), the pathway taken by the rainfall can be described as follows. The storm event simulated using the rain gage resulted in rainfall over the pavement near the RGs, the rooftop of the CEC, and directly above the RGs. Impervious surfaces such as the rooftop fed rainwater into the upstream manhole ("IN" in Fig. 9) and directly into RG 1. The concrete pavements also fed rainwater into the nearest RG, which then stored the rainwater until it either infiltrated into the native soil below or, if there was enough water volume present in the gravel layer, the water entered the perforated pipes running from RG 1 to RG 3 and drained into the downstream manhole ("OUT" in Fig. 9). While not visually illustrated in Fig. 9, both RG 2 and RG 3 contain a rock pit layer, extending the storage area available for retaining water.

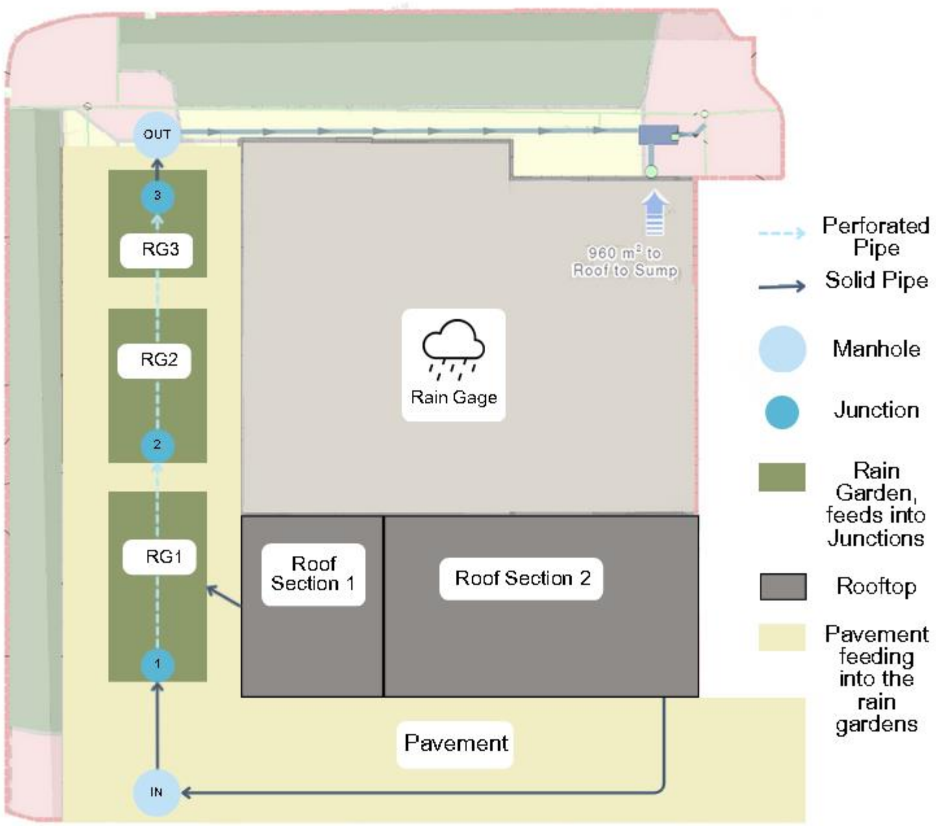

Figure 9. Illustration for the model setup in SWMM 5.2. Direction of rainwater flow was represented through blue (solid pipes) and dashed (perforated pipes) arrows. The semi-transparent backdrop for the model setup was adapted from the 2015 Nutrient Management Plan for the CEC site, arrows and information beyond Manhole OUT are outside of the scope of this study. Proportions in the illustration do not represent the dimensions of the study site in real-life. Manhole IN and OUT denote the upstream manhole and downstream manhole respectively.

From the upstream manhole, rainwater flowed through a solid pipe to the junction in RG 1, where the remaining inflow from the rooftop and the inflow from the rain gardens were added, then continued through RG 2 and RG 3 in a perforated pipe which allowed the water to infiltrate into the gravel layer of the rain gardens. At the junction in RG 3, the remaining rainwater in the pipes flowed through a solid pipe into the downstream manhole, before entering the rest of UBC's stormwater system. A visual representation of the water flow in the system is outlined in Fig. 10.

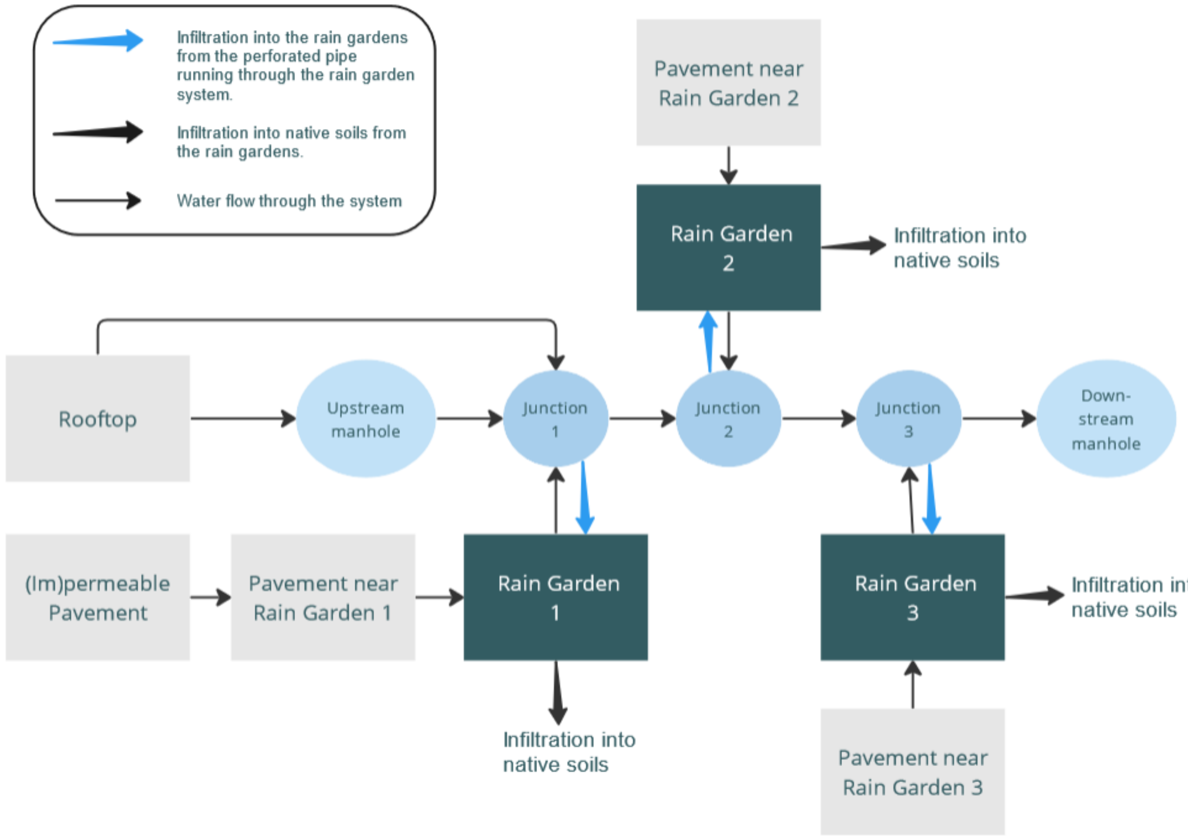

Figure 10. Flowchart mapping out the progression of water through the CEC RG system. (Im)permeable pavement represents a permeable pavement which has not been maintained since installation and assumed to have lost most of its function.

Model Assumptions

The pavement south of the rooftops and east of the upstream manhole in Fig. 9 was built to be another form of GRI: permeable pavement. However, the lack of maintenance since the installation of the permeable pavement has rendered the effectiveness of the LID structure non-existent (Razzaghmanesh & Beecham, 2018). Consequently, the model treated the permeable pavement as regular concrete pavement. In terms of the rooftop, the estimations of the rooftop area and resulting quantity of rainwater supply from the engineering drawing of the CEC were assumed to be true to life. Further assumptions made with respect to the model layout were addressed in Appendix A and Appendix C contains more information pertaining to the model setup.

Future Rainfall Data

The dataset used to design the storm events were sourced from Climate Data Canada (2024), which used historical precipitation data from the Vancouver Weather Station to scale rainfall rates, using an ensemble of 26 climate models (CMIP6) based on the 'business-as-usual' (SSP5-8.5) emission scenarios (Climate Data Canada, 2024). The temporal resolution for the projections used 30-year averages for the time frame of 2050-2080, and the rainfall rates were given in an Intensity-Duration-Frequencies (IDF) table, in mm/hr (Shephard et al., 2014). Of the projected values, the median rainfall rates were used, as shown in Table 3.

Table 3. IDF (intensity-duration-frequency) table for time range 2050-2080. Duration is the total duration of the storm. Frequency denotes the probability of a storm with certain magnitude occurring. Intensity of the rainfall rate (mm/hr) is given in the table and represents the peak intensity of a storm event. Climate change-scaled using the Clausius-Clapeyron equation (Climate Data Canada, 2024; Shephard et al., 2014). Highlighted values (yellow) indicate the storm events used in the model simulations.

Storm Duration	Storm Frequency					
	2 year	5 year	10 year	25 year	50 year	100 year
5 min	40.00	58.00	69.00	84.00	95.00	106.00
10 min	29.00	41.00	49.00	59.00	66.00	73.00
15 min	24.00	33.00	40.00	47.00	53.00	59.00
30 min	17.00	22.00	26.00	30.00	33.00	37.00
1 h	11.00	15.00	17.00	20.00	22.00	24.00
2 h	8.00	9.60	11.00	12.00	13.00	14.00
6 h	5.10	6.10	6.70	7.50	8.10	8.70
12 h	4.00	4.90	5.50	6.20	6.80	7.40
24 h	2.70	3.50	4.00	4.60	5.00	5.50

The highlighted rainfall rates in Table 3 (yellow) were used to create design storms with a frequency of 2-year, 10-year, or 100-year and a duration of 5 min, 1 hour, 2 hour, 12 hours, or 24 hours. The design storms were created using the triangular method (Ellouze et al., 2009; Weesakul et al., 2017) based on the IDF values, to produce a timeseries of rainfall intensity (mm/hr), as seen in the sample hyetograph (Fig. 11), and subsequently used in the model.

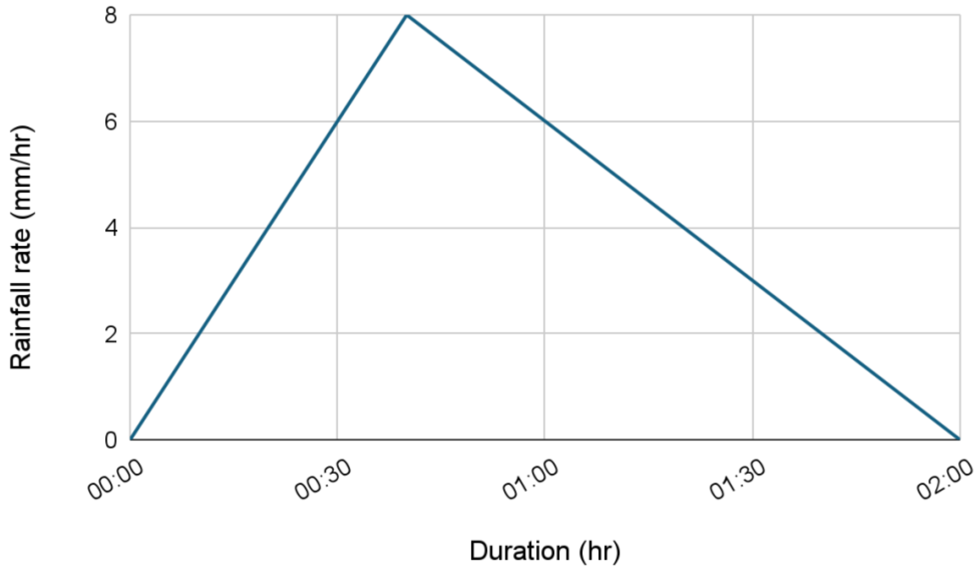

Figure 11. Sample design storm for a 2y - 2hr storm event using the triangular method. Rainfall rate (mm/hr) in the hyetograph denotes intensity.

Results

Performance Monitoring from January 25 to February 20, 2024

Assumptions for Performance Monitoring

- Rainfall events and intensities at the study site were assumed to be consistent with data observations from the ESB rooftop.
- Inlet flow rates were assumed to be the same across all RGs and calculated as the average of inflows measured at the two inlets.

Comparison of Total Inflow and Outflow

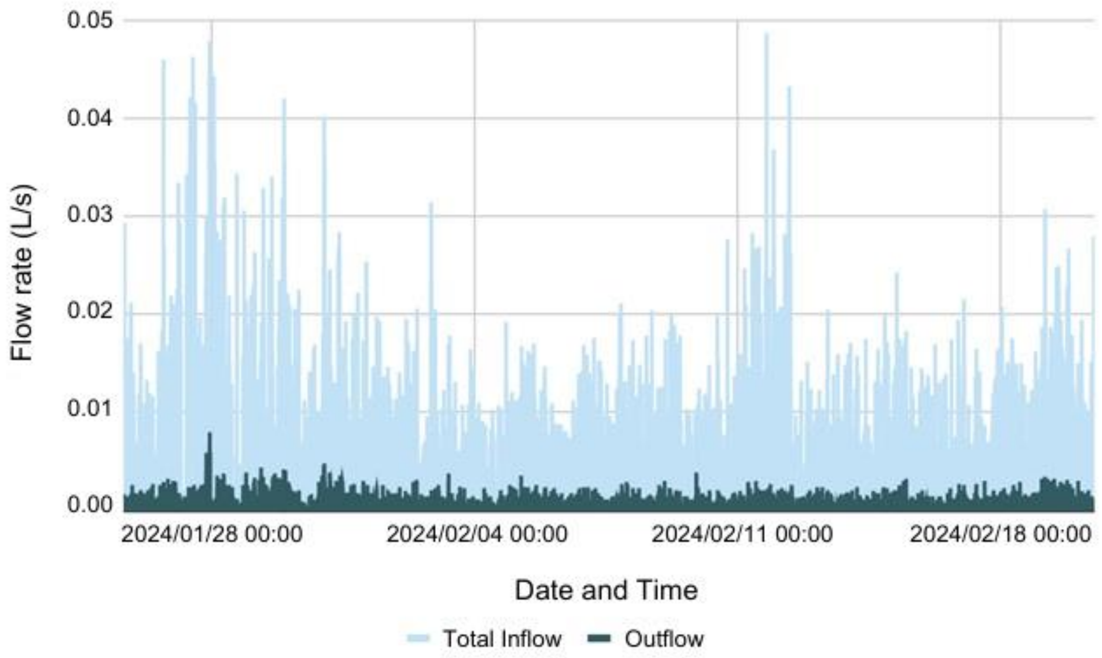

Figure 12. Total inflows and outflows (L/s) from the CEC RG system from January 25th, 2024 to February 20th,2024. Measurements were taken in 5-minute intervals. Total inflow is the sum of the total precipitation inflow, the initial inflow, and the water flow into the RGs. Outflow was measured through a logger placed in the manhole downstream.

In Fig. 12, outflow data showed minimal changes, with no instances of overflow observed in the CEC RG system across the observational period. This indicates the effective water absorption capacities of the CEC RG during this period. According to data from the ESB weather station, precipitation levels were relatively high in January and February of 2024, compared to the period from 2018 to 2024. This indicated that the CEC RG has managed to effectively reduce peak flow reduction against increasing precipitation in the months of January to February in recent years.

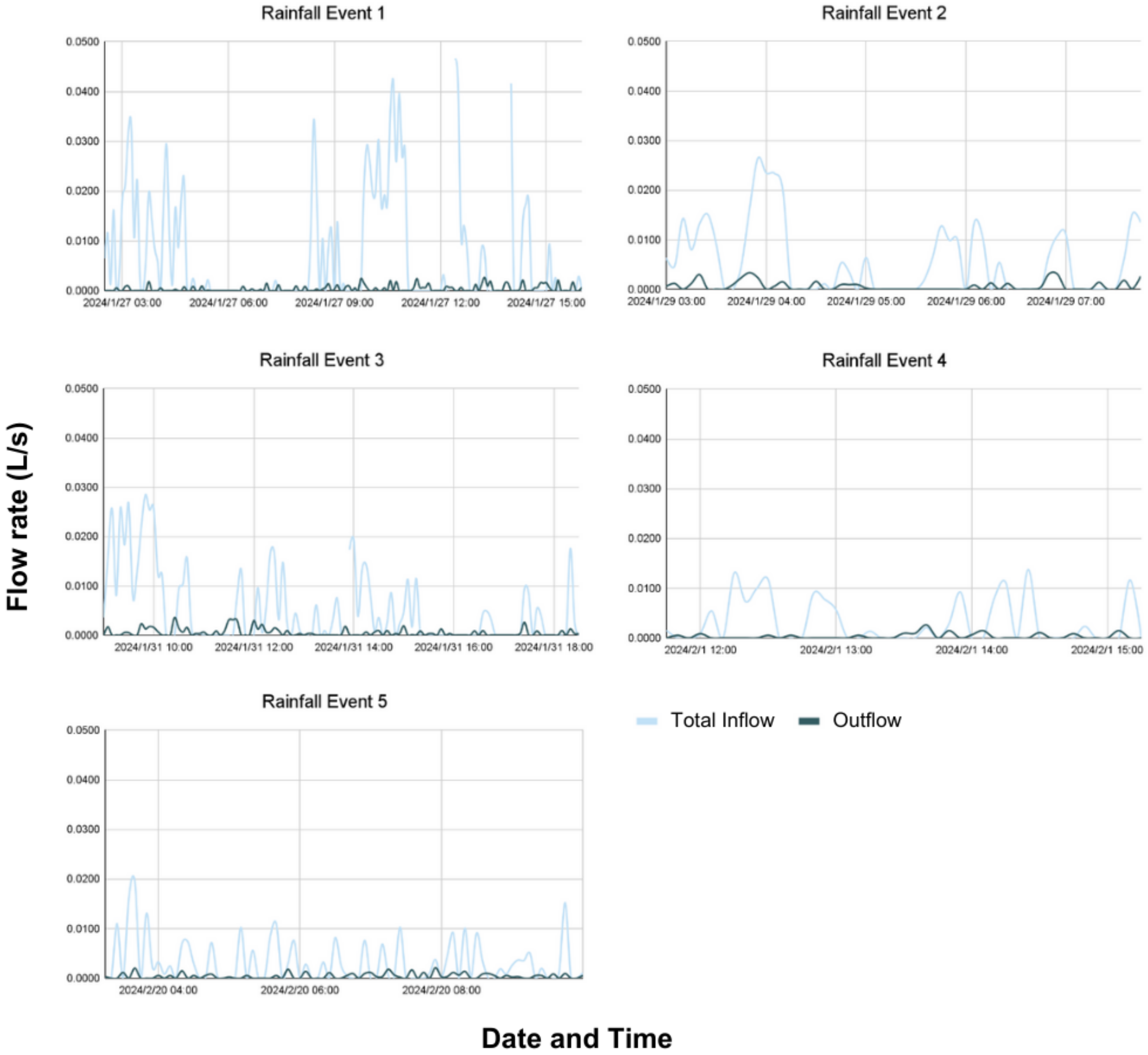

Figure 13. Comparison between inflow and outflow rates (L/s) for five segments of rainfall events occurring in the CEC RG from January 25th to February 20th, 2024. The time intervals for these events are as follows: January 27th , 2024 from 2:30 am to 4:00 pm; January 29th, 2024 from 3:00 am to 7:45 am; January 31st, 2024 from 9:00 am to 6:30 pm; February 1st , 2024 from 11:45 am to 3:15 pm, and from 3:15 pm to 7:45 am; January 31st, 2024 from 9:00 am to 6:30 pm; February 1st , 2024 from 11:45 am to 3:15 pm, and from 3:15 to 4:15 pm; and February 20th ,2024 from 3:15 am to 10:00 am.

Fig. 13 revealed that the differences in outflow rates from the outflow manhole were minimal, whereas variations in inflow rates were significant among the five rain events. Rainfall event 1 endured the longest, spanning from January 27, 2024, 2:30 am, to January 27, 2024, 4:00 pm, totaling 14 hours. During this period, the inflow rate peaked at over 0.045 L/s, indicating intense rainfall. In addition, rainfall event 5 had the shortest duration, lasting only about 7 hours from February 20, 2024, 3:15 am, to February 20, 2024, 10:00 am. The following box plot categorized and compared the intensity data of these five rainfall events.

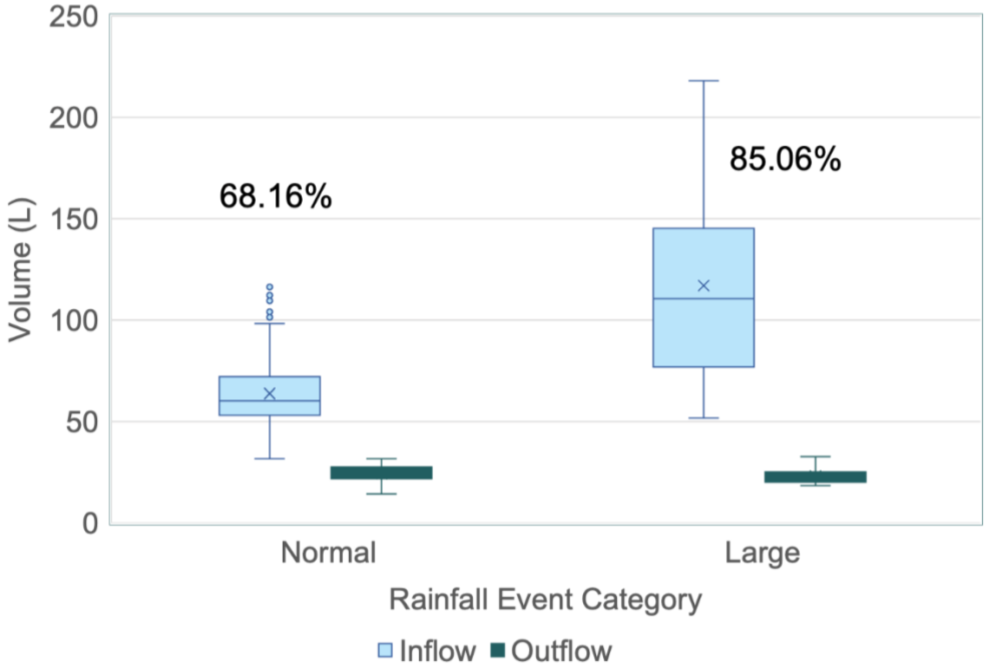

Figure 14. Boxplot of inflow and outflow volume and peak flow reduction (%) for different size rainfall events at the CEC rain gardens, including 4 normal and 1 large rainfall events. Volume (L) was calculated from total inflow which summed manhole upstream inflow volume, rainfall volume over RGs and CEC building rooftop and all inlets flow volume and outflow was the volume from manhole downstream. All manhole volume subtracted the original water volume maintained before placing the loggers in. The total volume of rainwater from start to end of a rainfall event. Peak flow reduction (%) was calculated with the following equation: $(Maximum\ Total\ Inflow - Maximum\ Total\ Outflow) \div Maximum\ Total\ Inflow$. All parameters used in normal events were averaged.

The box plot in Fig. 14 reveals significant differences between the two rainfall event categories as there is little to no overlap across both ranges of inflow and outflow. There was no extreme rainfall event observed during our data collection period. Within each category, inflow and outflow showed clear statistical differences. For normal events, the average inflow volume was around 60 L while the outflow was considerably lower, at around 27L. This is indicative of effective peak flow reduction. For the large event, compared to normal events, the average inflow volume was much higher (around 120L) than the outflow volume (32 L), indicating an even more effective peak flow reduction. The peak flow reduction was 68.16 % for normal events and 85.06% for the single large event. More details on the calculation for rainfall events are shown in Table 4.

Table 4. Summary table for rainfall events category of normal and large events within the parameters of number of events, rainfall duration (hr), total inflow and volume (L), and peak flow reduction. Parameters were averaged except for the number of events.

Rain Event Category	**Normal (under 24mm)**	**Large (between 24 and 48mm)**	**Total and average**
Number of Events	4	1	5
Rainfall Duration (hr)	6.1	14.5	10.3
Total Inflow Volume(L)	19007.1	19074.6	38081.8
Total Outflow Volume(L)	7213.2	3790.5	11003.8
Peak Flow Reduction	68.2%	85.1%	76.7%

Modelling

Peak Flow Reduction

Storm events with a storm duration of either 5 minutes, 1 hour, 2 hours, 12 hours, or 24 hours and a frequency of 2-year, 10-year, or 100-year were modelled in SWMM 5.2. The main metric examined was peak flow reduction, calculated as the difference between the peak total inflow into the storm management system and the peak outflow out of the system, as seen in Fig. 15 for a 12 hour, 10-year storm event.

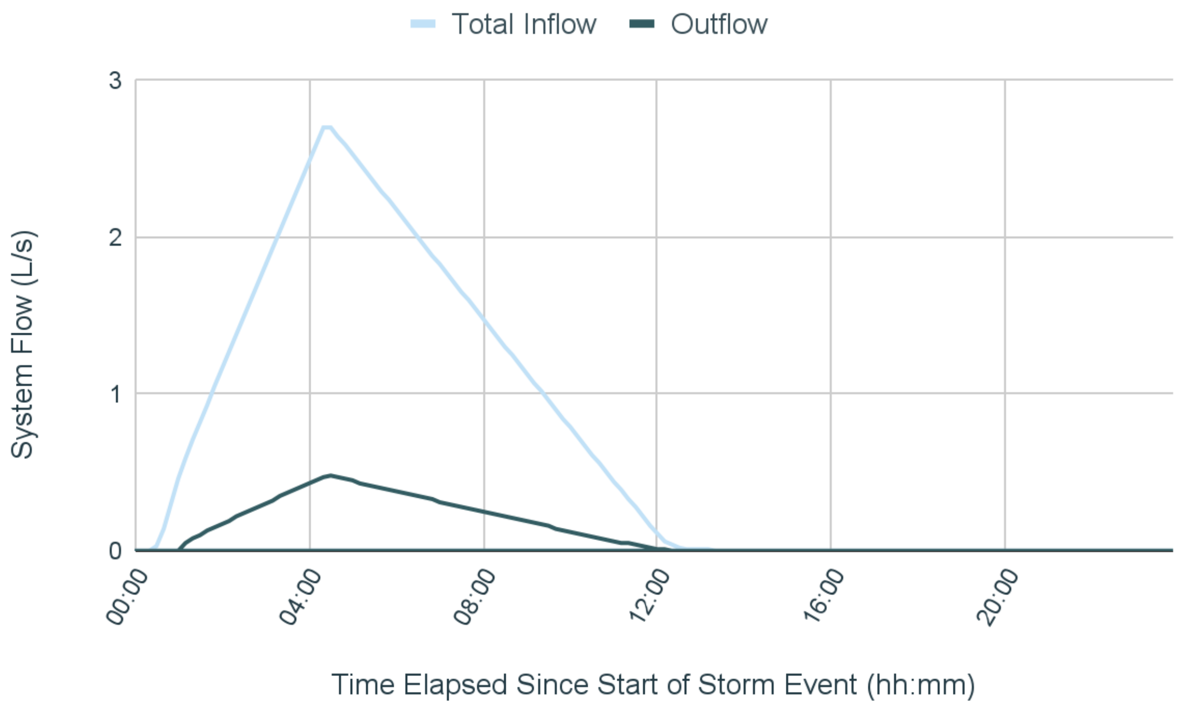

Figure 15. Comparison of total system inflow (L/s) and system outflow (L/s) over time elapsed since the start of the storm, for a storm event with a 10y return frequency and a 12h duration.

Peak flow reduction in the system has been given as a percentage in Fig. 16, where the shortest duration storms experienced the greatest peak flow reduction of above or near 90%. The longest duration storms, on the other hand, varied in peak flow reductions based on the storm frequency and subsequent storm intensity. Storm events with a duration ranging from 1 hour to 12 hours displayed comparatively similar peak flow reduction performance, hovering near 80%.

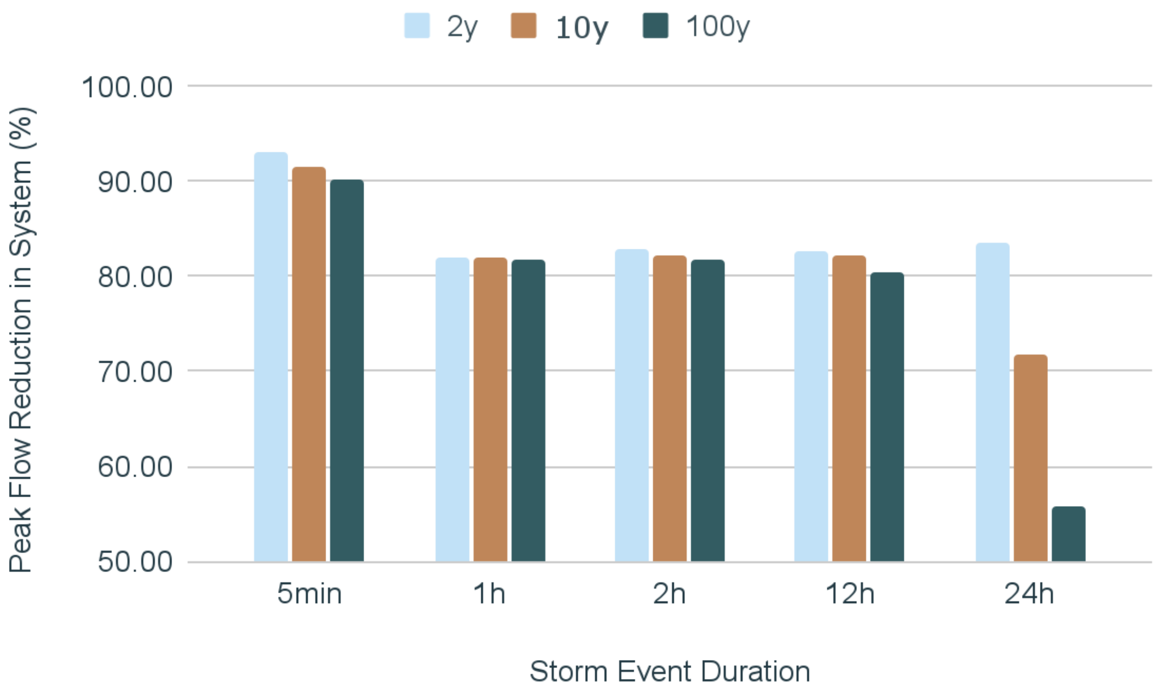

Figure 16. Peak Flow Reduction of the system (%) per each storm event. Storm events are characterized by storm duration by the frequency of the storm event. Storm frequency is given as 2-year events (light blue), 10-year events (brown), or 100-year events (dark green). Peak flow reduction was calculated using the peak total system inflow and the peak system outflow outputs generated in the SWMM model after running each storm event.

Supporting Metrics for LID evaluation

Table 5. described the proportion of runoff resulting from rainwater entering the rain gardens from the surrounding pavement with respect to the total precipitation entering the system. Most of the storm events indicated a high ratio of pavement runoff to total precipitation, with little variation among the storm events. The highest runoff to rainfall ratio was found for the 5 minute 2-year storm event while the lowest ratio was found for the 100y storm events with a duration of 5 minutes and 12 hours.

Table 5. Ratio of total pavement runoff to total rainfall entering the system. Colour gradient denotes higher runoff to rainfall entering the system with a darker shade of red. Only total pavement runoff (mm) was accounted for in the ratio. None of the model simulations resulted in runoff from the rain gardens.

Storm Event Frequency	Storm Event Duration				
	5min	1h	2h	12h	24h
2y	0.708	0.733	0.728	0.731	0.731
10y	0.726	0.735	0.730	0.732	0.732
100y	0.738	0.735	0.731	0.739	0.732

Table 6 described the percentage of rainwater which entered the rain gardens from either the surrounding pavements, directly from the rooftops, or through conduits in the stormwater management system yet was not stored by the rain gardens to be infiltrated into native soils. The color gradient illustrated a larger percentage of rainwater loss from the rain gardens' storage during storm events with a longer duration and larger frequency. The largest loss arose during the 24 hour, 100-year storm event in RG 1.

Table 6. Percent of total rainwater inflow into the rain gardens not stored by the RG (%). Total rainwater inflow (mm) includes precipitation directly entering the RGs, run-on from surrounding pavements, and inflow from the perforated pipe running through the RG system. Rain water (mm) stored by the RGs was obtained from the LID results of the model after each simulation per storm event. A darker shade of red in the colour gradient denotes a larger quantity of rainwater not stored by the RG system (%).

Storm Event Frequency	Rain Garden (No.)	Storm Event Duration				
		5min	1h	2h	12h	24h
2y	RG 1	0.00	13.19	14.93	5.35	3.54
	RG 2	0.00	0.00	0.00	0.24	0.73
	RG 3	0.00	0.00	0.00	3.49	8.39
10y	RG 1	0.00	8.55	13.06	3.97	15.80
	RG 2	0.00	0.00	0.00	1.40	8.25
	RG 3	0.00	0.56	0.00	12.53	7.33
100y	RG 1	0.49	6.07	10.30	10.31	38.78
	RG 2	0.00	0.31	0.00	9.76	7.93
	RG 3	0.00	4.77	0.21	10.02	5.86

Calculating Discrepancies between Real-Life and Model Results

To evaluate the model's accuracy, precipitation data from a real-life rainfall event on January 27th was entered into the SWMM model. Results from the simulation generated values for total inflow and outflow, which were then used to calculate peak flow reduction. Model results of the January 27th event yielded a peak flow reduction of 81.71% whilst real-life results from the primary data collection demonstrated a reduction of 85.01%. The difference between the observed and modelled peak flow reductions of the January 27th event is 3.3%, this could also be interpreted as the model's range of uncertainty.

Visual Observations

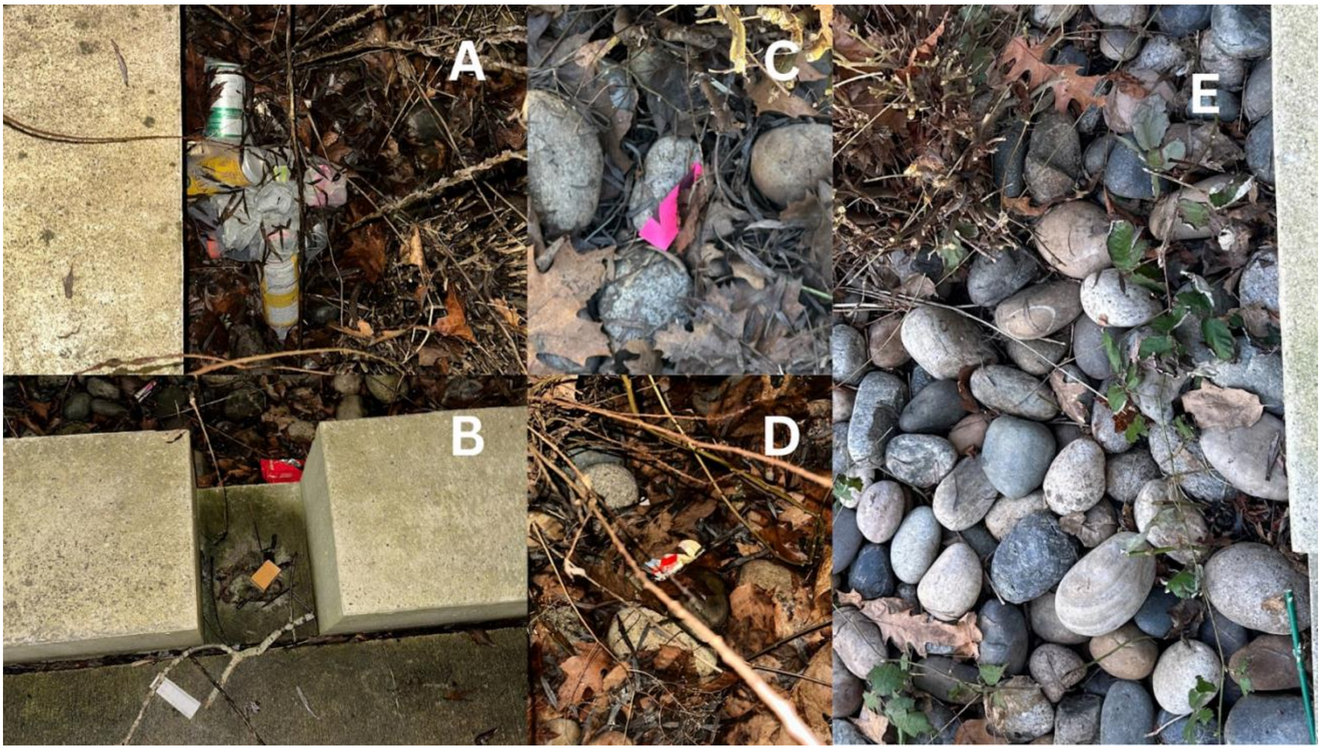

Figure 17. Examples of noticeable garbage, debris, and foreign plant species in the RG during the observational period (January 25 - February 20).

Photos A and B were taken on January 30, in RG 1 and RG 3, respectively shown in Fig. 17. The plastic bag of cans in A was present prior to the beginning of the observational period on January 28th, Both cases of litter were removed by February 1. Photos C and D were taken on February 2nd. The pink plastic waste in C was present in RG 1 until the end of the observational period on February 20th. Photo E shows a vine that was growing in RG 3. This vine was foreign to the RG as it was visually distinct to the species that was intentionally chosen in the RG design. It has been identified as potentially being a maple species (belonging to genus Acer).

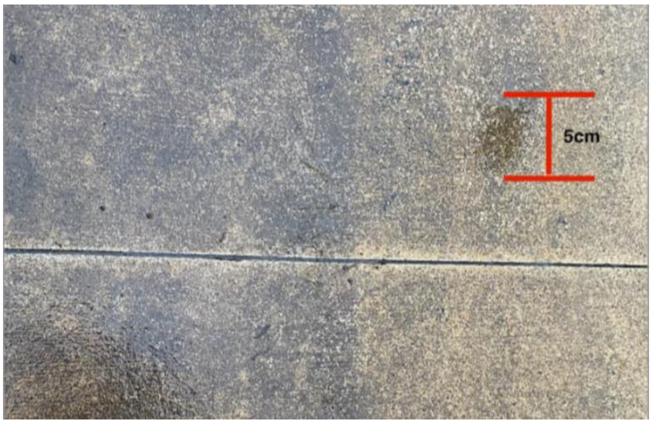

Figure 18. The photo of small ponding of 5 cm in length was taken on February 11th, 2024.

A small ponding was observed on February 11th as shown in Fig. 18. Based on data from the ESB Weather Station, the rainfall event started at 1:50 am. This near 20-hour rainfall event caused this small ponding to form on the pavement near the RG 1 inlet. During the entire observational period, there was no overflow observed across all RGs as there were no extreme rainfall events to pose the risk of overflow on the CEC RG system. A more detailed look into the observational data is in Appendix B.

Discussion

Summary of Findings

During the period of January – February 2024, primary data collection conducted on the CEC RG system demonstrated the system's capacity to mitigate normal to large rainfall events, as categorized in Table 1, evident in the significant peak flow reduction percentages for both (Fig. 14). The simulation results from the model built using the specifications of the CEC RG system in SWMM also described a similar capacity to reduce peak flow significantly under storm events varied in terms of both frequencies and in durations, while accounting for future projected increases in precipitation due to global warming in the 2050 – 2080 time range. Finally, the visual assessment for the CEC RG system noted accumulation of debris composed of biota from the vegetation present in the rain garden, as well as the presence of garbage within the rain gardens.

Field Experiment

As noted in the findings summary, the CEC RG system was capable of mitigating normal to large rainfall events, which were above the thresholds of 24 mm and 48 mm and had a peak flow reduction of 68.16% and 85.06% respectively. These values appear counterintuitive to what would be expected - a larger cumulation of rainfall volume should translate into a lower capacity for a GRI to capture and then store rainwater for infiltration into native soils, as seen with the bioretention cells and RGs present in the northeastern section of the UBC campus (Birch, 2023). However, this assumed that the limiting factor for peak flow reduction would occur due to the RG system's storage layer and berm layer being quickly overwhelmed. This was not the case for the CEC RG system, as both RG 2 and RG 3 were connected to a rock pit layer which lent additional storage space and all the RGs had an infiltration rate of 30 mm/h into the storage layer. Therefore, a smaller peak flow reduction occurred when a smaller quantity of rainwater was fed into the RGs, since the threshold for reduced peak flow reduction based on a high volume of rainwater was not reached during the study period.

While the first two months of 2024 experienced relatively more rainfall compared to the last few years (UBC Weather Summary, n.d), most of the rainfall to impact Vancouver and adjacent regions typically occurred during November and December. Therefore, the study period during which the data collection occurred did not represent the maximum rainfall volume the CEC RG system could expect, and further testing on the site during November or December may result in storm events above the threshold for extreme events (Table 1) to potentially overwhelm the system. Furthermore, the data collection period was less than one month long due to limitations in the budget, a longer period of study for a site could provide more recorded rainfall events, increasing the reliability and applicability of the findings. Finally, the years 2023 to 2024 experienced one of the strongest waves of El Niño on record, which manifested in the Pacific Northwest as drier, warmer winters (World Meteorological Organization, 2024; USDA Climate Hubs, n.d.). La Niña, on the other hand, typically resulted in increased precipitation and wetter winters, which should be taken into consideration when planning future primary data collection of peak flow reduction on GRIs under heavy rainfall scenarios (USDA Climate Hubs, n.d.). However, the current results could still be used as a baseline for comparison against other rain gardens or even other types of GRIs present in UBC in order to evaluate performance under normal conditions and with respect to the level of maintenance given.

Modelling Climate-Adjusted Rainfall Events

The modeled rainfall scenarios of varying rainfall intensity, duration, and frequency displayed a larger peak flow reduction of 90% during storm events with the shortest storm duration of 5 minutes, regardless of storm intensity. There was a decrease in peak flow reduction from a 5 minute storm event with a 2-year return period to one with a 100-year return period by 2.78%. For storm durations spanning from 1 hour to 12 hours, the peak flow reduction observed in the model simulations hovered around 80%, with the 12 hours storm event demonstrating a similar decrease in peak flow reduction by 2.16% from a 2-year to a 100-year event. As for the 24 hours storm events, peak flow reduction was drastically impacted by the storm frequency and subsequent intensity, with the difference of 11.74% and 27.72% in peak flow reduction occurring across the 2-year to 10-year events and the 2-year to 100-year events respectively.

Similar to the field experiment results, this trend can be explained by the total volume of rainwater which can enter the system without reaching the threshold where peak flow reduction would be negatively impacted under the modeled storm events. In this case, only the 24 hour duration storms accumulated enough volume when entering the CEC RG system to display large disparities in peak flow reduction across the varying storm event intensities (Fig. 16). However, it should be noted that not all of the rainwater impacting the impervious surfaces within the study area entered into the stormwater pipes or into the RGs, as seen in table 5. The relatively low ratio of total pavement runoff to total precipitation entering the system for storm events with a higher frequency and duration can also be attributed to a higher accumulation of total precipitation rather than a lower rate or volume of runoff. This assertion was supported by Table 6, which described the percentage loss of rainwater entering the RGs and not being stored, since higher frequency and duration storm events resulted in a larger loss of rainwater in terms of rainwater storage. Note that the infiltration loss from the rain gardens into the native soils was not accounted for in this metric and can be partially attributed to the larger loss in higher frequency and duration storm events, as infiltration has time to occur. Furthermore, RG 1 received comparatively more rainwater through the direct inflow the rooftop and had relatively less storage space than RG 2 and RG 3, which could also have attributed to the larger loss during higher intensity storm events.

The study results differed from Birch’s (2023) findings on rain gardens and bioretention cells in the North Eastern section of the UBC Vancouver campus. Subjected under climate-adjusted precipitation projections (Birch, 2023), the rain gardens were quickly overwhelmed during shorter duration and higher frequency storm events. The logic behind Birch’s model results was sound, since bioretention cells and rain gardens act primarily to capture and store rainwater from their respective catchment basins, then allow time for the native soils below the GRIs to slowly infiltrate down. Therefore, high intensity storm events over shorter durations resulted in more runoff compared to longer duration storms with lower intensities. However, in this study’s model, the opposite holds true. This could be attributed to numerous factors, including a difference in the scale of the studies as well as the model setup and metrics observed for evaluation. Furthermore, Birch may have used a different temporal scale for the precipitation data despite both studies using the same dataset (Climate Data Canada, 2024).

The resulting metrics from the CEC RG model can be used for comparisons against other rain gardens and forms of GRI present in UBC’s Vancouver campus, using the same climate-adjusted rainfall projections for the temporal period of 2050-2080 in a way larger-scale studies such as Birch’s (2023) cannot be. However, the CEC RG model can still be used for comparisons against larger-scaled models as well, provided that the metrics chosen and datasets used were consistent.

Visual Assessment

According to the visual observations conducted for the targeted RGs (RG1 and RG 2), the biggest finding was that the RGs tended to accumulate both plant debris and garbage due to lack of regular maintenance. However, the accumulation of debris in the inlets was not enough to significantly block water flow into the RGs. The only observed maintenance during the study collection period occurred halfway through the study period, when spring pruning of the vegetation occurred in all RGs and significantly decreased plant debris accumulation (Fig. 17). As demonstrated by the lack of ponding observed during the study period and the little to no impact on peak flow reduction, the CEC RG system did not require significant maintenance to function effectively. However, depending on the level of debris accumulation present in November during the La Niña cycle, further maintenance may be required.

Limitations

Unexpected Outcomes

The study's findings indicated an unexpected level of efficacy at the site in mitigating peak flow rates, even under the extreme storm conditions projected for a Representative Concentration Pathway 8.5 scenario. The results suggested that the site would remain highly effective in such rigorous environmental stressors.

Nevertheless, the interpretation of these outcomes necessitates an awareness of the model's inherent limitations. The model was constructed on a foundation of assumptions, which have been delineated in Appendix A. It was also noted that significant volumes of rainfall, which transitioned into pavement runoff, were not captured within the scope of field data collection and SWMM mode. This oversight signifies that the projected performance of the site might not encompass the entirety of the runoff dynamics, thus implying potential discrepancies between modelled predictions and real-world functioning.

Model Uncertainty Evaluation

The model’s uncertainty range was calculated as 3.3% after a comparison between the observed and model-projected peak flow reduction values of a rainfall event from January 27th. This uncertainty range suggests that the model is a somewhat accurate representation of real-life site performance as there are no large discrepancies between the real-life measurements and the model output. However, it is important to note that this uncertainty range solely addresses differences between the model and the primary data collection results and does not encompass uncertainties stemming from the data collection process itself. Consequently, if the data collection results are skewed or biased, the model’s accuracy could be compromised as well. The evaluation of uncertainties in the data collection process were unexplored, therefore, the extent of the primary data’s accuracy is unknown, and by extension the model’s accuracy is uncertain as well.

Limitations in Data Collection and Analysis

It should be noted that the primary data observations and results of this study are limited as there were only 5 recorded rainfall events during the collection period. A longer collection period with more events and data to analyze would most likely yield better results.

Furthermore, the design of the weir box may have caused inconsistencies in data collection. Measurements of water levels within the weir box design were subject to perturbations attributable to various factors. These perturbations were predominantly caused by the presence of soil fauna, such as earthworms and isopods, which could have altered the recorded levels. Moreover, the accumulation of debris, the impact of wind, and potential external interferences, such as the inadvertent tampering with the weir box setup by pedestrians, were identified as contributing factors to the measurement variability.

Regarding the structural components of the weir box, the cover was installed midway through the data collection phase. This alteration was considered to have potentially introduced minor inconsistencies in the measurements obtained before and after its installation. The impact of these inconsistencies was examined to ensure the integrity of the data collection process.

Implications for the wider UBC GRIs

The effectiveness of the CEC RGs at UBC illuminated the considerable potential of GRIs for the university's future urban development. These RGs serve as a beacon, showcasing how GRIs can be integrated into long-term stormwater management plans, especially with projected climate changes in mind.

UBC Campus and Community Planning professionals, encompassing engineers and urban planners, are advised to integrate the insights gained from the CEC RGs into their forthcoming urban development strategies. The benefits are twofold: practical and multi-dimensional. On a practical level, GRIs contribute to diminishing the volume and flow of stormwater entering the sewage system, alleviating the strain on the existing stormwater infrastructure. This reduction in water load is instrumental for sustainable campus development.

Beyond the practical, the GRIs harbour a spectrum of social, economic, and ecological advantages. Eronen et al. (2021) delved into these aspects, highlighting how the aesthetic enhancement from NbS and GRIs can elevate the visual allure of the campus environment. This beautification not only augments the campus's charm but also enriches the experiences of residents and visitors alike, fostering a more inviting and enjoyable campus atmosphere.

Nonetheless, it is crucial to acknowledge that the optimization of GRIs' benefits is inextricably linked to their upkeep. Effective maintenance is the linchpin that ensures the continued success and functionality of these infrastructures within the campus ecosystem. Without ongoing care, the full suite of benefits that GRIs offer may not be realized, underscoring the importance of diligent stewardship in their implementation.

Recommendations

Based on the visual assessment criteria from the Toronto and Region Conservation Authority report (2016), the detailed practices outlined in the "Condition Assessment Handbook," and the Nutrient Plan, the following recommendations are proposed for the maintenance and enhancement of the CEC rain gardens within the larger context of SEEDs/C+CP initiatives on campus. These recommendations aim to prepare the rain gardens for the challenges posed by projected future extreme weather events.

Recommendations for Action

Immediate Actions:

- Debris and Sediment Management:
    - Implement a maintenance schedule for systematic removal of litter and natural debris post-rainfall events to prevent inlets from clogging.
    - Responsible Party: Facilities Management
    - Timeline: Immediate response post-event, within 24 hours.

Mid to Long-term Actions:

- Fertilization and Landscaping (cited from Nutrient Management Plan from UBC District Energy Centre):
    - Prioritize the use of adaptive vegetation to reduce the need for fertilization.
    - Employ low-phosphorus and slow-release fertilizers based on soil testing to prevent over-fertilization.
    - Responsible Party: Campus Landscaping Department
    - Timeline: Planning to commence in the upcoming planting season and review biennially.
- Cleaning Practices:
    - Advocate for water-only cleaning methods and the use of environmentally friendly cleaning agents with safe levels of phosphorus when necessary.

  - Responsible Party: Campus Facilities and Groundskeeping
  - Timeline: Adopt new cleaning protocols within the next 3 months.
- Infrastructure Inspection and Repair: Schedule bi-annual inspections of the RG infrastructure for any signs of damage or erosion, particularly focusing on inlets, outlets, and perimeter curbing. Prioritize repair work based on the severity of damage to maintain functionality.
  - Responsible Party: Campus Infrastructure Services
  - Timeline: Every six months, with repairs scheduled according to urgency.

Recommendations for Future Research

Longer deployments of data collection periods:

- The current data collection period was too short to make conclusive evidence for evaluating the performance of the RG system. Getting more data on reduction with different times of year can help generate more reliable and conclusive outcomes on performance of RG systems.
- Recommended Research Group: Future ENVR 400 students on this project; Campus + Community Planning groups
- Timeline: Extended the data collection period to at least one year.

GRI Performance under Future Climate Projections:

- Investigate the performance of various types of Green Rainwater Infrastructure (GRI), such as swales, green roofs, and rain gardens, using future climate projections. Assess how changes in precipitation patterns might affect their efficiency and develop adaptation strategies for their design and management.
- Recommended Research Group: School of Architecture and Landscape Architecture (SALA) and Department of Civil Engineering.
- Timeline: Preliminary research to start within the next year, with ongoing adaptation and resilience studies over a 5-year period.

Water Quality Monitoring Studies:

- Initiate a continuous water quality monitoring program that evaluates the water exiting the rain gardens. This program would examine the effectiveness of the rain gardens in removing contaminants and nutrients from stormwater runoff and would provide essential data for calibrating maintenance practices to enhance water purification outcomes.
- Recommended Research Group: Hydrology within the department of Forest Resources Management.
- Timeline: Baseline studies to be established in the upcoming rainy season, with reports due every six months.

Conclusion

The CEC rain gardens demonstrated a significant capacity for peak flow reduction during the rainfall events of January to February 2024, underscoring their effectiveness in managing stormwater on-site. Through a detailed analysis of inflows and outflows, it was observed that the rain gardens efficiently absorbed water, with no instances of overflow recorded during the monitored period. This indicated that, for the conditions tested, the CEC rain gardens were an effective GRI solution for mitigating immediate surface runoff and reducing flood risks associated with medium-intensity rainfall events.

It was important to note that the rainfall during the recorded period was not particularly heavy. As a result, the water storage in the RG did not reach its peak capacity during this period. Consequently, the study period may not have fully captured the water absorption capabilities of the RG under extreme weather conditions. Despite this limitation, the observed performance indicated a positive water-absorbing effect during the given time frame, as demonstrated by the peak flow reduction in the overall RG system. For further field-based research, coordinating a data collection period in November or December which receive noted heavy downpours in Vancouver may rectify this limitation.

A similar result was observed when modelling the CEC RG system’s peak flow reduction performance under climate-adjusted precipitation projections. The RG system was not overwhelmed during short-duration, high-frequency, and high-intensity storm events as was initially expected but demonstrated a larger reduction in peak flow. This demonstrated that the RG system had not yet reached its full capacity to store rainwater. Though this threshold may be reached under climate-adjusted rainfall projections for a more distant timeframe such as 2080-2100 instead of the timeframe used in this study (2050-2080), where rainfall intensity was anticipated to increase even further under a RCP8.5 emissions scenario. However, it should be noted that the high percentage of peak flow reduction did not translate into significantly diminished runoff rates or volume in the model, and a high proportion of rainwater still became runoff. Should the CEC RG system be used as a baseline for rain garden or GRI performance on the UBC Vancouver campus, then the metrics for both peak flow reduction and the runoff ratio could be useful in conducting a comprehensive evaluation of LID performance.

Furthermore, after incorporating insights from existing literature by the City of Vancouver and observations made during data collection, the aforementioned set of recommended actions and their respective frequencies for maintaining the CEC RG have been produced. This plan would help guarantee the functionality of the rain garden's water absorbency, particularly in the face of extreme precipitation, and also ensure the quality of stormwater inflow to UBC’s sewage system.

Overall, the CEC RGs have effectively managed stormwater during the study period, undergoing moderate rainfall events. Projected increases in precipitation due to climate change did not significantly impact the RG system’s ability to mitigate peak flow, and the simulations echoed the trends observed in the field experiment. Further research should assess the effectiveness and performance of CEC RG system within a longer data collection period to better apply the recommendations produced by this study into the wider scope for the campus’ GRI.

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SHA256&X-Amz-Credential=AKIA4KKNQAKIOR7VAOP4%2F20231212%2Fca-central-1%2Fs3%2Faws4_request&X-Amz-Date=20231212T044402Z&X-Amz-Expires=300&X-Amz-SignedHeaders=host&X-Amz-Signature=d867d73d37de8af75238899fa6a30830ad6b475ec8c95b7ad79cefcc4a2c6912

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Appendices

Appendix A. SWMM Model Assumptions

Assumption 01. The soil type within the RGs was assumed to be sandy loam. Table 1 in the CEC Nutrient Management Plan outlines the percent of dry weight mineral fraction (%) in the RG to be 50-70 for Sand and max. 30 for Clay and Silt combined. Using these values, the soil texture class was identified using the following method published by the USDA NRCS:  Since the SWMM software was developed in the US, US-based soil texture classification was used for the model. Input values for these parameters were outlined in Table A.2 Soil Characteristics of the US EPA SWMM 5.2 User Manual (Lewis A. Rossman & Simon, 2022).
Assumption 02. Site specific values for dimensions of sub catchments, elevations of inverts, and other pipe specifications were sourced from engineering drawings of the CEC buildings (including but not limited to '521-05-006, SITE SERVICING ONSITE STORMWATER & STANDARD DETAILS'). All structures are assumed to be built per design.
Assumption 03. The engineering drawing titled "521-05-006, SITE SERVICING ONSITE STORMWATER & STANDARD DETAILS" states that the material used in the rock infiltration zone is "50mm TO 75mm CLEAN, CRUSHED ROCK, CONTAINING NO FINES, WITH VOID RATIO >35% (ASTM No.57)." ASTM No. 57 is the stone specifications code by the American Society for Testing and Materials International (ASTM). According to a fact sheet by the manufacturing company TRUEGRID Pavers (n.d.), the void ratio of ASTM No. 57 is 0.40.
Assumption 04. According to the SWMM 5.2 User Manual (Lewis A. Rossman & Simon, 2022), the seepage rate is the rate at which water seeps into the native soil below the layer and can be found as the saturated hydraulic conductivity of the surrounding sub catchment when using Green-Ampt infiltration. Since the model is using Mod-Green-Ampt, the saturated hydraulic conductivity is used for the soil type of the rain gardens (sandy loam). The seepage rate is then sourced from Table 5.3 in the Storm Water Management Model Reference Manual - Hydrology (Rossman & Huber, 2016)
Assumption 05. Estimates of area for pavement determined by overlaying engineering drawings of the site onto the site's location on Google Earth are assumed to have negligible differences from actual dimensions of the site. This

method was employed due to a lack of information from the engineering drawings corresponding to the site and due to an outdated aerial view of the site on Google Earth as of 2024.

Appendix B. Visual Assessment Data Collection Sheet

Date	Time	Area of Concern	Picture?	Notes
01/28/2024	20:32	Garbage	☑	Bags of garbage in both RG 1 & 2
01/28/2025	20:35	Debris	☑	Some leaves on the top of the weir box in RG#1
01/28/2026	20:35	Ponding	☐	No obvious ponding
01/29/2024	22:11	Ponding	☐	No obvious ponding
01/29/2024	22:11	Debris	☑	Some leaves in inlet #1
01/29/2024	22:11	Garbage	☐	Bags of garbage in both RG 1 & 2
01/30/2024	17:38	Debris	☑	Some leaves on the pavement around RG 1 Inlet, not obstructing inlet itself. None around RG 2.
01/30/2025	17:38	Ponding	☑	No ponding
01/30/2025	17:38	Garbage	☑	Garbage present in all three RGs.
01/31/2024	12:23	Debris	☑	Big renovations for rain garden no 1 (plants on site got cut, introducing more plant debris in the form of branches).
01/31/2024	12:23	Ponding	☑	No ponding
02/01/2024	17:58	Debris	☐	Some leaves run into the both weir box
02/01/2024	17:58	Ponding	☐	No ponding
02/02/2024	17:20	Ponding	☐	No ponding
02/02/2024	17:20	Debris	☑	Light to minimal leaves around RG 1 inlet.
02/02/2024	17:20	Garbage	☑	Small pieces of plastic garbage are present in RG 1 & 2.
02/03/2024	22:27	Ponding	☐	No ponding
02/03/2024	22:27	Debris	☑	Some leaves run into the both weir box
02/03/2024	22:27	Garbage	☐	All the garbage has been cleaned up.
02/04/2024	19:29	Ponding	☐	No ponding
02/04/2024	19:29	Garbage	☐	No garbage in either RGs.
02/04/2024	19:29	Debris	☑	Some leaves in inlet #1, few leaves in inlet#2.
02/05/2024	17:03	Ponding	☐	No ponding
02/05/2024	17:03	Debris	☐	Some leaves run into the both weir box
02/05/2024	17:03	Garbage	☐	All the garbage has been cleaned up.
02/06/2024	17:13	Ponding	☐	No ponding
02/06/2024	17:13	Debris	☑	Light to minimal debris around RG 1 inlet.
02/06/2024	17:13	Garbage	☐	No garbage in either RGs.
02/08/2024	17:48	Ponding	☐	No ponding
02/08/2024	17:48	Debris	☐	Debris accumulation inside weir box
02/08/2024	17:48	Garbage	☐	No garbage in either RGs.
02/09/2024	16:52	Ponding	☐	No ponding
02/09/2024	16:52	Debris	☐	A lot of leaves in inlet #1, few leaves in inlet#2.
02/09/2024	16:52	Garbage	☐	No garbage in either RGs.
02/10/2024	16:45	Ponding	☐	No
02/10/2024	16:45	Debris	☑	Little leaves in RG 1, no in RG 2
02/10/2024	16:45	Garbage	☑	Slightly in RG 1, no in RG2
02/11/2024	16:07	Garbage	☐	No garbage in either RGs.
02/11/2024	16:07	Ponding	☑	Two small pondings on the pavement in RG1
02/11/2024	16:07	Debris	☐	Some leaves within the inlet#1, none in RG2
02/12/2024	15:20	Ponding	☐	No ponding
02/12/2024	15:20	Debris	☑	Some leaves within the inlet#1, none in RG2
02/12/2024	15:20	Garbage	☐	No
02/13/2024	14:27	Ponding	☐	No ponding
02/13/2024	14:27	Debris	☑	A lot of leaves in inlet #1, few leaves in inlet#2.
02/13/2024	14:27	Garbage	☑	There's some garbage in RG1 and RG2.
02/14/2024	14:23	Ponding	☐	No ponding in either RG
02/14/2024	14:23	Debris	☐	Some leaves within the inlet#1, none in RG2
02/14/2024	14:23	Garbage	☐	No
02/16/2024	23:06	Ponding	☐	No
02/16/2024	23:06	Debris	☑	Yes, some leaves on inlets in RG1
02/16/2024	23:06	Garbage	☑	Yes, garbage was shown in RG1
02/17/2024	23:23	Ponding	☐	No ponding
02/17/2024	23:23	Debris	☑	A lot of leaves in inlet #1, few leaves in inlet#2.
02/17/2024	23:23	Garbage	☑	There's some garbage in RG1 and RG2.
02/18/2024	20:50	Ponding	☐	No ponding
02/18/2024	20:50	Debris	☑	A lot of leaves in inlet #1, few leaves in inlet#2.
02/18/2024	20:50	Garbage	☑	There's some garbage in RG1 and RG2.
02/19/2024	16:07	Ponding	☐	No ponding
02/19/2024	16:07	Debris	☑	A lot of leaves in inlet #1, few leaves in inlet#2.
02/19/2024	16:07	Garbage	☑	There's some garbage in RG1 and RG2.

Appendix C. SWMM Model.inp File

```
CEC Model
April 06 Version

[OPTIONS]
;;Option           Value
FLOW_UNITS         LPS
INFILTRATION       MODIFIED_GREEN_AMPT
FLOW_ROUTING       DYNWAVE
LINK_OFFSETS       DEPTH
MIN_SLOPE          0
ALLOW_PONDING      YES
SKIP_STEADY_STATE  NO

START_DATE         03/31/2050
START_TIME         00:00:00
REPORT_START_DATE  03/31/2050
REPORT_START_TIME  00:00:00
END_DATE           04/01/2050
END_TIME           06:00:00
SWEEP_START        01/01
SWEEP_END          12/31
DRY_DAYS           0
REPORT_STEP        00:01:00
WET_STEP           00:01:00
DRY_STEP           01:00:00
ROUTING_STEP       0:00:20
RULE_STEP          00:00:00

INERTIAL_DAMPING   PARTIAL
NORMAL_FLOW_LIMITED BOTH
FORCE_MAIN_EQUATION H-W
VARIABLE_STEP      0.75
LENGTHENING_STEP   0
MIN_SURFAREA       1.167
MAX_TRIALS         8
HEAD_TOLERANCE     0.0015
SYS_FLOW_TOL       5
LAT_FLOW_TOL       5
MINIMUM_STEP       0.5
THREADS            1

[EVAPORATION]
;;Data Source    Parameters
;;-------------- ----------------
CONSTANT         0.0
DRY_ONLY         NO

[RAINGAGES]
;;Name           Format    Interval SCF      Source
;;-------------- --------- ------ ------ ----------
Gage1            INTENSITY 0:01     1.0      TIMESERIES 100y5min

[SUBCATCHMENTS]
;;Name           Rain Gage        Outlet           Area     %Imperv  Width    %Slope   CurbLen  SnowPack
;;-------------- ---------------- ---------------- -------- -------- -------- -------- -------- ----------------
RG1              Gage1            J1               0.008908 1        10       0.5      0
RG2              Gage1            J2               0.007344 1        15       0.5      0
RG3              Gage1            J3               0.005848 1        15       0.5      0
P1               Gage1            RG1              0.018331 100      11       0.5      0
P2               Gage1            RG2              0.005407494845 100      11       0.5      0
P3               Gage1            RG3              0.01016550515 100      11       0.5      0
R1               Gage1            RG1              0.01574  100      13       0.5      0
R2               Gage1            M_IN             0.03445  100      14       0.5      0
PP               Gage1            P1               0.047628 100      57.6     0.5      0

[SUBAREAS]
```

```
;;Subcatchment   N-Imperv   N-Perv    S-Imperv  S-Perv    PctZero    RouteTo    PctRouted
;;-------------- ---------- ---------- ---------- ---------- ---------- ---------- ----------
RG1           0.012     0.06      0.1       0.2       25       OUTLET
RG2           0.012     0.06      0.1       0.2       25       OUTLET
RG3           0.012     0.06      0.1       0.05      25       OUTLET
P1            0.012     0.1       0.1       0.05      25       OUTLET
P2            0.012     0.1       0.1       0.05      25       OUTLET
P3            0.012     0.1       0.1       0.05      25       OUTLET
R1            0.015     0.1       0.05      0.05      25       OUTLET
R2            0.015     0.1       0.05      0.05      25       OUTLET
PP            0.012     0.1       0.12      0.05      25       OUTLET

[INFILTRATION]
;;Subcatchment   Param1     Param2     Param3     Param4     Param5
;;-------------- ---------- ---------- ---------- ---------- ----------
RG1           109       70        0.263
RG2           109       70        0.25
RG3           109       70        0.25
P1            3.0       0.5       4         7         0        HORTON
P2            3.0       0.5       4         7         0        HORTON
P3            3.0       0.5       4         7         0        HORTON
R1            3.0       0.5       4         7         0        HORTON
R2            3.0       0.5       4         7         0        HORTON
PP            109       70        0.26

[LID_CONTROLS]
;;Name           Type/Layer Parameters
;;-------------- ---------- ----------
rg23          BC
rg23          SURFACE    300       0.01      0.05      1.0       5
rg23          SOIL       300       0.453     0.19      0.085     70        42        109.982
rg23          STORAGE    740       0.35      0.508     0         NO
rg23          DRAIN      0         0         0         6         0         0

rg            BC
rg            SURFACE    300       0.01      0.05      1.0       5
rg            SOIL       300       0.453     0.19      0.085     70        42        110
rg            STORAGE    13        0.75      0.508     0         NO
rg            DRAIN      0         0         0         6         0         0

[LID_USAGE]
;;Subcatchment   LID Process      Number  Area       Width      InitSat    FromImp    ToPerv     RptFile                  DrainTo
FromPerv
;;-------------- ---------------- ------- ---------- ---------- ---------- ---------- ---------- ------------------------ ---------------- ----------
RG1           rg          1      89.08     0         0         0         0         *                  J1           0
RG2           rg23        1      73.44     0         0         0         0         *                  J2           0
RG3           rg23        1      58.48     0         0         0         0         *                  J3           0

[JUNCTIONS]
;;Name           Elevation  MaxDepth   InitDepth  SurDepth   Aponded
;;-------------- ---------- ---------- ---------- ---------- ----------
M_IN          95.31     1.22      0         0         0
J1            95.25     1.22      0         0         0
J2            95.245    1.22      0         0         0
J3            95.2445   1.22      0         0         0

[OUTFALLS]
;;Name           Elevation  Type       Stage Data       Gated    Route To
;;-------------- ---------- ---------- ---------------- -------- ----------------
M_OUT         95.2      FREE                        NO

[CONDUITS]
;;Name           From Node        To Node          Length     Roughness  InOffset   OutOffset  InitFlow   MaxFlow
;;-------------- ---------------- ---------------- ---------- ---------- ---------- ---------- ---------- ----------
C1            M_IN          J1            13.4       0.015     0         0         0         0
C2            J1            J2            19         0.015     0.00045   0.00025   0         0
C3            J2            J3            20         0.015     0         0         0         0
C4            J3            M_OUT         3.9        0.015     0         0         0         0
```

```
[XSECTIONS]
;;Link          Shape        Geom1            Geom2      Geom3      Geom4      Barrels    Culvert
;;-------------- ------------ ---------------- ---------- ---------- ---------- ---------- ----------
C1              CIRCULAR     0.15             0          0          0          1
C2              CIRCULAR     0.15             0          0          0          1
C3              CIRCULAR     0.15             0          0          0          1
C4              CIRCULAR     0.15             0          0          0          1

[LOSSES]
;;Link          Kentry     Kexit      Kavg       Flap Gate  Seepage
;;-------------- ---------- ---------- ---------- ---------- ----------
C2              0          0          0          NO         30
C3              0          0          0          NO         30


[REPORT]
;;Reporting Options
SUBCATCHMENTS ALL
NODES ALL
LINKS ALL

[TAGS]

[MAP]
DIMENSIONS -1690.480 -232.092 10386.891 10000.000
Units      None

[COORDINATES]
;;Node          X-Coord            Y-Coord
;;-------------- ------------------ ------------------
M_IN             2129.346           355.021
J1              2129.346           2057.219
J2              -1141.509          5064.255
J3              -1141.509          7058.837
M_OUT            2086.069           8462.096

[VERTICES]
;;Link          X-Coord            Y-Coord
;;-------------- ------------------ ------------------

[Polygons]
;;Subcatchment   X-Coord            Y-Coord
;;-------------- ------------------ ------------------
RG1              2691.936           1956.241
RG1              2648.660           4047.924
RG1              1552.330           4062.349
RG1              1552.330           1927.390
RG2              2677.511           4509.536
RG2              2634.235           6240.584
RG2              1537.904           6255.010
RG2              1566.755           4552.813
RG3              2634.235           6716.622
RG3              2648.660           8159.162
RG3              1523.479           8144.737
RG3              1552.330           6759.899
P1              1018.590           4466.260
P1              1018.590           210.767
P1              3095.847           181.917
P1              3110.273           4480.686
P1              1004.164           4480.686
P2              3139.124           4480.686
P2              3139.124           6702.197
P2              1004.164           6716.622
P2              1004.164           4509.536
P3              3124.698           6687.772
P3              3124.698           8260.140
P3              989.739            8260.140
P3              989.739            6702.197
R1              4870.171           1595.606
```

```
R1             4855.746          3874.819
R1             3110.273          3860.393
R1             3124.698          1610.031
R2             8577.499          1638.882
R2             8577.499          3860.393
R2             4870.171          3860.393
R2             4884.597          1624.457
PP             3104.355          192.415
PP             9837.920          207.054
PP             9837.920          1641.596
PP             3104.355          1626.958
PP             3104.355          207.054

[SYMBOLS]
;;Gage          X-Coord           Y-Coord
;;-------------- ------------------ ------------------
Gage1           5778.972          5923.226

[LABELS]
;;X-Coord         Y-Coord           Label
3982.646          2358.867          "R1" "" "Arial" 10 0 0
6119.821          2329.591          "R2" "" "Arial" 10 0 0


[BACKDROP]
FILE       "swmm bg.png"
DIMENSIONS -92.166 0.000 10092.166 10000.000
```

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