THESIS

QUANTITATIVE ANALYSIS OF RUNOFF IN GREEN ROOF STRUCTURES IN THE COLORADO FRONT RANGE

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ABSTRACT

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The green roof capacity of retaining rainwater extends the runoff duration further than the actual rain event, releasing part of it slowly into the drainage system and positively impacting it. However, the volumes will depend on the size of the rainfall event and the green roof design. Therefore, specific attention should be paid when designing a new green roof project, like geographic locations, materials peculiarities, and the project's needs, including biotic and abiotic design components.

The need for more local data regarding this analysis in Western North America is still significant. Therefore, this study aims to analyze the impact of three different green roof systems on Colorado's climate by reduction of runoff, retention volume, and runoff coefficient. Moreover, we aim to analyze plant health and substrate moisture retention and components for better water capture.

To achieve the goals outlined, three different green roofs technologies, with different retention and detention layers technologies, and a control roof, a conventional low slope roof for comparison, are placed at Colorado State University in Fort Collins, Colorado, United States; the systems include a Sempergreen Purple Roof, a Sempergreen Sponge Roof, and a Green Roof Technology with an Extenduct Drainage System; all were vegetated with Sedum mats, base slopes of 1% toward the rooftop drain, and measuring 1m x 2m. The drainage systems in each green roof were designed to test performance under steady, low-intensity, high-intensity, short-duration, and long-duration rainfall conditions and simulated rain events. All the systems have the same drain system connected to a v-notch weir. Volume, speed, and time were measured to quantify the runoff from all roof systems.

Our data suggests that green roof volume capture varies with preexisting substrate moisture conditions, frequency and size of storms, and drainage layer components. Green Roof Technology with an Extenduct Drainage System and Sponge Roof had the best volume retention in less intense, more frequent, and back-to-back rainfall events. On the other hand, Purple Roof performed better for larger rain events that might lead to flooding and urban drainage concerns in cities. Ultimately, the Colorado-specific data from this study will enable the intentional design of green roofs to optimize plant health and water management.

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1. Introduction

In the past years, cities worldwide have been suffering from extreme temperatures (heat islands), floods, indiscriminate development, deforestation, population growth, and other environmental damage. The city and county of Denver, Colorado, covers 401.4 km^2 and is home to an estimated population of 715,522 (U.S. Census Bureau, 2021) and is part of an even larger metropolitan area. Denver weather is considered semi-arid with hot summers, with a mean annual temperature in 2020 of 11.3 ◦C, 1.8 degrees above the normal yearly average. In 2020 Denver had a total of 222mm of precipitation, the 9th driest year in Denver since 1872. An average annual snowfall of 2.54m occurred between September 20–April 21 (National Weather Service, 2020). With the current situation, to meet a minimum equilibrium between climate change and water demand management in urban centers, it is imperative to integrate land use and water planning with stormwater management. This would promote intervention of the urban heat island, social and cultural benefits of green space, and equitable housing (Blount et al., 2021).

Urban areas have more runoff water volume due to their impervious surfaces, which prevents the water from infiltrating, and a majority of these impervious surfaces are roofs. According to the City and County of Denver (2021), several Denver neighborhoods suffer from floods during rainstorms or after very wet winters. More extreme flooding is also possible in lower-lying areas of town, including some residential areas because of their proximity to a significant waterway and they are at increased risk of flooding. To better manage these risk areas, the Mile High Flood District (MHFD) and their contractors design and build flood control and warning measures, removing trash and debris in streams in the Denver area. They create flood hazard maps and provide data and support to the floodplain administrators, providing notifications of heavy rain and flood threats, ensuring local knowledge of the stream and potential flood risks.

Flooding in urban areas happens because impervious surfaces do not allow rain or snowmelt to infiltrate onsite, directing this runoff to storm conduits. When the runoff reaches the storm sewer conduits, it gains velocity and the power to erode soil, which can damage streamside vegetation and destroy aquatic habitat. Canalization and low water infiltration increase floods during and immediately after rainfall events. Moreover, during dry weather, it can result in even lower stream flows. Additionally, this runoff carries many pollutants, like sediments, oil, grease, toxic chemicals, pesticides, and heavy metals, to streams and rivers, harming wildlife populations, native vegetation, drinking water supplies, and negatively affecting recreational areas. Therefore, infiltration in urban areas can protect the surface and underground watersheds from serious harm (USEPA, 2003).

Green roof projects can be used as an effective and accomplishable technology to increase permeable surface areas in cities, promoting a reduced amount of stormwater runoff. Its capacity to retain rainwater extends the runoff duration over a period further than the actual rain event, releasing part of it slowly to the drainage system (VanWoert et al., 2005). Moreover, vegetating rooftops minimizes the vegetated footprint removed when the building is constructed (Getter & Rowe, 2006). In addition, green roofs provide the owners of buildings with a proven return on investment. Adding green roofs also represent significant social, economic, and environmental benefits, particularly in cities, which positively impact heat islands, manage stormwater, remove airborne pollutants from the air, and provide many other benefits (Greenroofs.org; Fioretti et al., 2010).

Europe has a green roof market very well established. Many of the factors that led to this advance are the direct result of government legislation and financial support. Creating, in this way, a strong and well-structured market for green roof products and services (Greenroofs.org). On the other hand, the lack of accessible and public data in many cities in North America makes the benefits of green roof technologies flawed and misunderstood. MHFD created an urban storm drainage criteria manual to inform practitioners in the Denver metro region about Best Management Practices (BMPs), including green roofs. However, there are regional gaps in the available data for the stormwater volume capture of green roofs and their system components. This research will fill this gap in information about green roofs and stormwater management in the Western North American semi-arid climate.

2. Objectives

Green roofs can retain significant amounts of rain, which positively impacts urban drainage systems. However, the volumes captured will depend on the size of the rainfall event, the size of the green roof, and the green roof design and components. Therefore, specific attention should be paid to these factors when designing a new green roof project.

Furthermore, details to achieve particular functions will vary between geographic locations, material peculiarities, and the project's needs, including biotic and abiotic design components (Simmons et al., 2008). The lack of data and information about green roofs in North America, especially in the western half of the continent, compared to other countries in Europe and parts of Asia, addresses a need for quantifiable data about green roofs and stormwater management in such specific climatic conditions. Much of Europe's data and regulations are not applicable in North America (VanWoert et al., 2005).

Therefore, this study aims to analyze the impact of three green roof systems, providing data about the effectiveness of green roofs in stormwater capture on Colorado's climate. Evaluating the reduction of runoff volume and its delay, retention volume, and the runoff coefficient of these green roof systems. Moreover, analyzing plant health and substrate performance in terms of soil moisture retention and components for higher water capture.

3. Literature Review

3.1 Increase in urbanization, decrease in green spaces, and hazards.

Urbanization is a complex process involving social, cultural, and economic agents, transforming formerly rural areas into urbanized spaces. It is a known fact that the world population is growing, and with it, so are our cities. According to the United Nations (2018), more than half of the world's people live in urban areas. And it is projected that by 2050 around 68 percent of our population will live in cities.

Rapid urbanization, lack of planning and management, lack of control from public institutions, unsustainable production and consumption, and inadequate investments from private and public sectors can negatively impact sustainability due to urban sprawl, pollution, and environmental and health degradation (United Nations, 2018). Around 60% of cities across the world face high risks of exposure to natural disasters, like cyclones, droughts, floods, earthquakes, landslides, and volcanic eruptions. With that, Sustainable Development Goal 11 from United Nations, Sustainable Cities and Communities, are responsible for making cities more inclusive, safe, resilient, and sustainable. Sustainable urbanization includes disaster risk reduction, sustainable cities, and human settlements, which promote sustainable land-use planning and management, and integrated provision of environmental infrastructure such as water, sanitation, drainage, and solid waste management (United Nations, 2018).

Increasing urbanization, and consequently impervious surfaces, and the impact of climate change require nature-based solutions. Specifically, urban green infrastructure solutions and sustainable strategies to increase resilience against extreme weather events, especially stormwater runoff flooding. Implementing green infrastructure solutions can reduce the impact of stormwater floods. Green roofs help detain water and decrease stormwater runoff impacts on a local scale (Twohig et al., 2022).

The strategy to green the urban environment can be an essential tool to solve problems related to urban densification and meet the United Nations Sustainable Development Goals. Green infrastructure solutions, like green roofs, have multiple environmental, social, and economic benefits that improve buildings' performance and the urban environment, such as citizens' health and well-being, biodiversity, aesthetic value, recreational use of space, and urban farming (Manso et al., 2021).

3.2 Green Roof Definition

Green roof systems are an extension of the existing roof, basically built with a waterproofing membrane, root repellent system, drainage system, filter layer, substrate, and plants (Green Roofs for Healthy Cities). Green roofs can be also called eco-roofs, living roofs, planted roofs, or vegetated roofs. Green roofs use plants to improve a roof's performance and aesthetics. Green roofs are often described as intensive, which has a substrate depth of 15 cm or deeper, or extensive, which is shallower than 15 cm of substrate (Snodgrass & McIntyre, 2010).

Intensive and extensive green roofs are distinct in substrate depth, plant material, and planned usage for the roof area. Intensive green roofs are systems that usually will require more vegetation maintenance, which can be more diverse and labor-intensive to maintain. Intensive green roofs can be designed similarly to garden areas, with various plants and deeper substrate layers. However, extensive roofs generally require minimal maintenance. One of its features is that it is easily installed in more sloped areas. Usually, extensive green roofs have a shallow substrate and a more limited variety of plants. Often extensive green roofs are designed to be in non-accessible spaces (Getter & Rowe, 2006).

The construction components are usually the same for both types of green roofs, such as waterproofing membrane, root repellent system, drainage system, filter layer, substrate, and plants. However, when the project goals are more specified and aligned, factors such as intended use, and local weather, can inform the selection of the particular the components. Typically, on top of the waterproof membrane, a root barrier is installed to protect the roof from root penetration damage. A drainage layer above the root barrier allows excess water to be detained, increasing water holding capacity or allowing it to flow away from the roof, avoiding excess moisture on the plant root level. On top of the drainage layer is the filter fabric that filters particulate matter and prevents clogging. Finally, the substrate and vegetation are added on top of all other layers (Getter & Rowe, 2006).

Another definition used for green roofs, based on their stormwater management specificity, is blue-green roofs. This term is defined as a green roof where its combined components provide stormwater management. The drainage layer promotes water detention in the system, an essential feature to increase the runoff delay and promote a greater peak flow reduction (Andenæs et al., 2018). Also, blue-green roofs allow more stormwater to be stored because the reservoir can act as a water source for the vegetation throughout capillary rise (Busker, 2022) and plant root hydraulic lift (Caldwell et al, 1998).

3.3 Green Roof Survivability

3.3.1 Vegetation

Plants in green roof systems provide much more than aesthetics. They are an essential part of the green roof project's success, such as increasing biodiversity, pollinator provisioning, and more. However, on a rooftop, stressors are more intense than on the ground. For example, high heat, greater wind velocity, and harsh sunlight can challenge the vegetation. In this case, it is important to select plants that establish quickly and live for a long time (McIntyre & Snodgrass, 2010). An important consideration for green roof vegetation is that the volume of water detained from a stormwater event in the substrate becomes a water resource and should be recognized when designing for the water quality capture volume (UDFCD, 2010).

On a green roof, the plants need to have a root system that binds the substrate together, with a horizontal continuity, throughout all the seasons, preventing wind scour and improving function and efficiency, and reducing maintenance. Sedum plants are typically chosen for green roofs due to the fact that they are light in weight, transplant well, tolerate a wide range of conditions, have lateral root systems, have low nutrient and maintenance requirements, are resistant to insects and diseases, and do not spread through windborne seeds (McIntyre & Snodgrass, 2010).

Sedum's ability to change its metabolism, adapt to droughts, and change back when there is moisture allows it to survive when other plants would not. As a CAM (Crassulacean Acid Metabolism) plant, during the day, the stomata are closed, which prevents water loss through transpiration, conserving water in its tissues. Stomata open at night, when it is cooler and more humid, allowing CO_2 to enter and be fixed in the mesophyll cell cytoplasm by a PEP reaction (McIntyre & Snodgrass, 2010; Sage, 2008).

Common methods to plant sedums on a green roof are cuttings, plugs, and/or seeds. A less complex way is using pregrown mats, which establish very quickly, and makes them easy to move and replace. More cuttings will mean quicker cover, and a mix of species will allow for greater adaptation success and provide a diversity of colors and textures (McIntyre & Snodgrass, 2010).

3.3.2 Substrate and Soil Moisture

The ideal substrate is crucial to meet the expected performance of the roof, the goals, the structural capabilities, and the vegetation's needs (Stewart, 2009; Dunnett and Kingsbury, 2004). The substrate choice must balance factors such as being light in weight, well-drained, good aeration, adequate water, and nutrient-holding capacity and include materials that will not break down over time (Getter & Rowe, 2006).

Among the materials, the most abundant component should be mineral based, such as expanded slate, shale, clay, sand, perlite, pumice, vermiculite, and/or biochar. Mineral-based materials have a sponge-like appearance, which creates voids to hold air and organic material and increase the particle's surface area, promoting a slow movement of water. Organic matter is recommended at low levels for extensive green roofs; however, it decomposes and increases levels of N and P in runoff water (Getter & Rowe, 2006; McIntyre & Snodgrass, 2010). Also, using topsoil can introduce pests and pathogens into the green roof system (Dunnett and Kingsbury, 2004).

The substrate is a crucial component for green roof success, plant health, irrigation needs, and further stormwater benefits. Extensive green roofs usually use lightweight aggregates, which typically drain very quickly. For intensive green roof applications, the substrate can include materials with higher water retention characteristics, such as organic matter, while still considering the saturated weight for structural design calculations (UDFCD, 2010).

The uniqueness of the water-substrate relationship says a lot about the right choice for the substrate. Water content and water potential vary for substrates, where physical properties describe the different states of the water in the substrate. The state of water in the substrate is the amount of water and the energy associated with the forces which hold the water in the substrate, depending on the substrate temperature, chemical transport, vegetation, and water availability. The amount of water is defined by water content, and the energy state of the water is the water potential (Bilskie, 2001).

The water movement intercepted by the vegetation and retained will depend on the substrate but also on the vegetation type and properties. A portion of the water is held by the plant roots and uptake by the plants after it has infiltrated into the substrate. The behavior of the water depends on many factors. When the force of gravity exceeds suction forces, the remaining portion moves downward in the substrate. The water moving in the substrate, through saturated to unsaturated substrate, is called the wetting front. However, not all the water will drain through the substrate to the drainage layer, some part of it is retained in the substrate due to its capillary suction force. The maximum amount of water that a substrate can hold within its structure against the pull of gravity is called the field capacity of the substrate (She and Pang, 2010).

Water content indicates how much water is present in the substrate, it can be measured by gravimetric water content or volumetric water content. This can estimate the amount of water retained in the substrate or how much irrigation is required (Bilskie, 2001). The field capacity is the ratio between the maximum volume of water retained in the substrate and its total volume (Cassel & Nielsen, 1986). She and Pang (2010) show examples in green roofs; some water will move to pass the wetting front through the substrate and drain to the drainage layer before the substrate is completely saturated.

Contrary to what is expected, the substrate needs to be completely saturated before the water drains through it and reaches the drainage layer. What is occurring is a dual process in the substrate; when its moisture content is between field capacity and saturation, some water continues to advance the wetting front and some moves through the substrate to the drainage layer. This movement of water is because the upward capillary force of water in the larger voids of the substrate is exceeded by gravity, while the capillary force of water in smaller voids can resist the pull of gravity. Only after the substrate has become completely saturated does the moisture content equal the porosity. Consequently, Darcy's Law is demonstrated when the suction force in the substrate vanishes and the water flows through the substrate.

The hydrological hypothesis is that on a green roof, after a rain event, the water is retained in the substrate layer and other lower layers, and the vegetation will help use water through transpiration. If the soil moisture is below field capacity and the rain event is not intense, there is a chance of no runoff from a green roof system. However, after field capacity is reached, the runoff will probably happen. When runoff occurs from mild rain events of long duration, it indicates that the substrate has achieved a saturated point.

The substrate moisture can remain close to field capacity over extended periods, depending on its location, climate, and weather. It is normal that in the summer, on drier days, the substrate dries out between rain events. Sometimes it can take a few days for the substrate to dry to near wilting point conditions. Then, when a storm occurs, rainwater is stored in the substrate and vegetation until field capacity is reached, initiating a runoff event. When the rain ceases, the water on the roof, which is over field capacity, is drained by gravity. Further reduction of water retention is attributed to evapotranspiration. (Bengtsson et al, 2005).

Evapotranspiration can be used as an indirect measure of substrate moisture. Indicating the water retention capacity of the substrate between precipitation events and the need for irrigation. Selecting high-water-use plants can be a good strategy to increase the dryness of the substrate and allow for more volume for water retention. However, in dry climates, this strategy may compromise the green roof and demand extra irrigation (Talebi et al., 2019). Evapotranspiration occurs during dry periods, and the seasonal variation can result in a variation in the runoff reduction, with the highest reduction during summer and the lowest during winter (Bengtsson et al, 2005).

All the factors together, such as substrate choice, plant selection, lower layer selection to increase water retention, the local climate, and structural applications, can influence the substrate moisture conditions, the potential water detention, reduction of runoff, and the need for irrigation.

3.4 Green Roof Benefits

Urbanization brings many detrimental impacts on society and the environment, partly attributable to the conventional use of roofs on buildings. In the U.S., the majority of the building sector comprises impervious black or dark-colored roofs that absorb roughly 80% of sunlight. With the number of conventional roofs and streets with dark surfaces, the city's heat is considerably increased, creating an urban heat island (Akbari et al., 2001).

The absorbed sunlight heat from conventional roofs not only increases cooling costs in air-conditioned buildings but also increases discomfort in unconditioned buildings and increases mortality during heat waves and air pollutants. Therefore, green roofs are introduced in the construction industry as a more beneficial solution to society and the urban environment to reduce public health hazards (Sproul et al., 2014).

Green infrastructures, like green roofs, have multiple associated environmental, social, and economic benefits that improve buildings' performance and the surrounding urban environment. To achieve the benefits and use a green roof as a tool in the sustainable construction arsenal, it is necessary to have a clear design intent, considering both the regional climate and the roof's microclimates, proper installation, and a maintenance program to ensure long-term viability (McIntyre & Snodgrass, 2010).

Potential benefits can include stormwater management and quality of stormwater runoff. In addition, longer life for the roof membrane, protecting it from UV damage, reduced amplitude of diurnal thermal cycling (expansion and contraction), and roof punctures. As well, reduction in energy costs, providing extra insulation reducing the transfer of heat into the space below. By reducing energy consumption, green roofs reduce the emission of air pollutants and greenhouse gas emissions (GHG) from power plants, potentially mitigating global warming and improving urban air quality. Green roofs can also help on the mitigation of urban heat island effect, when implemented on a broad scale. Furthermore, promote habitat for urban wildlife, and increase vegetation footprint. Also increase amenity value, like aesthetics, marketing, and increase developable space, for example a garage underneath it, as the green roof won't occupy a space as another stormwater management structure (Getter & Rowe, 2006; McIntyre & Snodgrass, 2010; Sproul et al., 2014; Velazquez, 2005).

Some benefits are included in all types of green roofs, while others are designed for a specific benefit. Most practitioners divide the benefits into public or private. Public benefits include waste diversion, reduction of the urban heat island effect, improved air quality, increased biodiversity, educational opportunities, and local job creation. Private benefits are aesthetic improvement of the building, energy efficiency, stormwater management, integrated water management, increased membrane durability, fire retardation, enhanced photovoltaic performance, new amenity spaces and property value, blockage of electromagnetic radiation, noise reduction, marketability, improved human health and well-being, and urban agriculture. Besides these two categories, public and private, it is important to note that most benefits can also fit both categories such as stormwater management (GRHC, 2013).

3.5 Green Roofs and Stormwater Management Practices

When designing a green roof for stormwater management proposes, it is crucial to consider local specificities such as: weather factors, rain intensity and duration, substrate depths and composition, and plant species. Those factors will strongly correlate with the water retention volume of green roofs and plant survivability (Getter & Rowe, 2006). Moreover, specific substrates with more absorption capacity, drainage layers, or modular panels combined with drainage system to store water while still allowing the removal of excess water, can increase the benefits associated with water retention (Cascone, 2019).

These aspects and features contribute to the most often cited environmental service of green roofs, stormwater management. It happens by reducing peak flow, releasing the outflow water at a slower speed and smaller amount (Getter & Rowe, 2006). However, for a green roof to better perform as a stormwater management tool, it needs to be able to hold as much water as possible without damaging the vegetation and generating overload in the structure. For that, it is essential to consider the right structure of a green roof because the frequency, intensity, and duration of a storm event cannot be controlled (Rowe & Getter, 2022).

Even though green roofs can provide many benefits, most policies and incentives for green roof installations are for stormwater management. A proper green roof design reduces the load on municipal water and sewer infrastructures, prolonging their life expectancy and reducing costs associated with inspection, repair, environmental clean-ups, and expanding new conduits. Their public and private benefits can reduce the chances of combined sewer overflow (CSO) events, decrease flooding, and increase the quality of runoff water. Its quality is improved by reducing the amount of surface contaminants like debris, chemicals, oils, and sediment that can harm rivers, streams, lakes, and coastal waters, which can cause changes in hydrology and water quality, resulting in habitat modification and loss, increased flooding, decreased aquatic biological diversity, and increased sedimentation and erosion (Rowe & Getter, 2022; Green Roofs for Healthy Cities, 2013; EPA, 2023).

The water movement on the green roof has a predictable behavior. The rainfall is intercepted by the plants, reaches the substrate, and underneath layers, the portion of water that remains on the substrate and vegetation can return to the atmosphere by evaporation. However, the portion of water that infiltrates underneath layers depends on the type of rainfall and weather conditions, the substrate characteristics, previous moisture content, and the type of vegetation selected (She and Pang, 2010).

The previous moisture content of the substrate can affect the retention capacity of the green roof, but because of substrate specificities and other layer configurations, brief dry periods and high temperatures can significantly reduce the substrate moisture content and allow the green roof to reduce the runoff resulting from a rainfall event (Cardno TEC, 2012). Even though green roof substrate has a point of saturation, where it stops retaining stormwater and runoff occurs, runoff is still delayed, slowing down its runoff, which can help with erosion control of runoff that does enter streams either through direct runoff or storm sewers. This delay can prevent stormwater sewer systems from overflowing by allowing them to process runoff longer at a lower flow rate (Getter & Rowe, 2006).

The drainage layer is crucial in a green roof design for stormwater management. This layer drains the excess water from the substrate, allowing proper ventilation for the roots, as most of the vegetation needs a ventilated and non-waterlogged substrate. This function of draining extra water decreases the load on the building structure and reduces the risks of a roof collapse. Usually, the drainage layer is made with modules to store water during rain and make it available during drought periods; by evaporation and capillary forces, it reaches the above layers and the substrate (Cascone, 2019).
The choice for the best drainage layer varies according to local rainfall characteristics, construction needs, structural requirements, costs, green roof size, roof slope, quantity and flow of discharges, and plant species, also on the hydraulic flow and the vertical load (Cascone, 2019). A green roof doesn't need to take over the entire rooftop area to add a great impact on stormwater management, it can be designed to accept runoff

from a conventional roof area. This can be done with a slow controlled release, providing water quality for an extra area of the green roof and also for irrigation benefits (UDFCD, 2010).

Some studies already show that green roofs can improve stormwater management. VanWoert et al. (2005) found that during light rain events (<2mm), their green roof model-scale started the runoff 55 minutes after the measurement of an initial rainfall, reducing in this way the peak flow. Also, during heavy events (>6mm), the runoff was delayed and spread over time, with the last runoff measured almost 3 hours after the end of the rainfall, which on a big scale can help reduce flood risks. Furthermore, VanWoert et al. (2005) show that their green roof could retain 337mm of 556mm of cumulative rainfall for over 14 months; it is a 60.6% efficiency.

In this same study, VanWoert et al. (2005) recorded the heaviest rainfall of 100% retention from their green roof in a 5.56mm rain event. For this event, the substrate was low in moisture as the five previous days had no precipitation and had an average temperature of 29.8 °C, which is comparable to the weather in the Denver area. The National Weather Service (2020) at Denver International Airport Station shows that in May, the wettest month, had an average of 4.65mm of rain, four days without precipitation between rain events, and temperatures reaching 29.4 °C.

In Vancouver, Canada, Connelly and Liu (2005) monitored an established green roof with 75mm substrate for 30 days. On day 12, with an event of heavy rainfall, 12.19 mm of rain for over 4 hours, the green roof retained 95% of runoff. No rainfall was recorded in the previous 11 days for this rain event. However, on day 13, two medium rain events were registered, and the green roof had a retention rate of 44% and 52%, respectively. On the following 2 days, retention decreased to 17% and 20%, with two rain events of over 30 mm of rainfall over more than 16 hours each. Even with the point of saturation of the substrate and the heavy rain events, the green roof retained 67% of the rainfall over the 30 measured days.

Runoff reduction and delay are necessary for stormwater management. However, the total amount of water and rain is not often the problem for stormwater management, but the rate at which the inflow water reaches the system and needs to be treated. Reduction in overall quantity also leads to better stormwater runoff and surface water quality. VanWoert et al. (2005) compared two extensive green roof treatments, one vegetated and the other substrate-only. They show that the treatments are not significantly different from the rain events, suggesting that the main factor in retaining water is the physical substrate properties and water retention fabric. However, vegetation is essential to prevent erosion from wind and water, promotes transpiration, cooling, and shade for the building, and helps mitigate urban heat islands.

In Augustenborg, Malmö, Sweden, the stormwater from roofs and other impermeable and semi-permeable surfaces has been disconnected from a CSO to reduce the annual runoff and the runoff peaks. In this case, the goal is to have the stormwater handled locally and the runoff reduced as much as possible. With this strategy, and the use of green roofs to detain rainwater, the intention is to reduce the stormwater runoff from Augustenborg into the CSO system by at least 70%. (Bengtsson et al. 2005).

3.6 Challenges about climate, environment, and water availability in the Front Range area.

Colorado's climate is configurated by its interior continental location in the middle latitudes, the high elevation of the entire region, with mountains and ranges extending north and south, crossing the middle of the state. It is considered the highest contiguous state in the Union. With elevations ranging from below 7,000 feet in the lower mountain valleys to more than 14,000 feet on the highest peaks, all aspects of the climate are affected, such as temperature, humidity, precipitation, and wind. The mountainous area of central and western Colorado produces differences in climate over short distances. In general, its combination of high elevation and middle latitude results in a cool and dry climate, with large seasonal swings in temperature and large diurnal changes. In addition, Colorado is a headwater state, which means that all rivers in Colorado rise within its borders and flow outward, except the Green River, with four of the nation's major rivers, the Colorado, the Rio Grande, the Arkansas, and the Platte (Nolan et al., 2003).

Precipitation patterns are largely controlled by mountain ranges and elevation. The statewide average annual precipitation is 17 inches. High peaks and mountain ranges generally receive most of their precipitation during winter, accumulating snow that will melt in the spring. Most of the mountain snow melts during May and June which causes rivers to reach their peak for the year. This snow is the primary source of water for much of the population of the state and provides water for extensive irrigation. However, as climate change continues, the snow is melting earlier, resulting in water scarcity in late summer. Also, this change in the scenario can result in a runoff and peak flows occurring earlier, leading to more frequent flooding events, especially in disturbed areas (CWCB,2019; CWCB, 2023; Nolan et al., 2003).

Floods are the most common and widespread of all natural hazards in Colorado. Flood-prone areas have been identified in 267 Colorado cities and towns and in all 64 counties. Some floods develop slowly, but flash floods can happen in minutes. One of these events was a flood in 2013 that resulted in nearly $4 billion in damages, reaching 20 counties in Colorado. Also, the infamous Big Thompson Canyon flood of July 31, 1976, occurred in a vulnerable area. And many others resulting in a devastating number of deaths and damages (CWCB, 2023; Nolan et al., 2003).

The increasing temperatures, shifts in snowmelt runoff, water quality concerns, stressed ecosystems, improper infrastructure, impacts on energy demands, and extreme weather events that can impact air quality and recreational opportunities are the consequences that will affect the residents of Colorado and beyond. However, because the effects of climate change can enhance existing stressors, it has a disproportionately negative impact on more vulnerable populations due to social, political, and economic inequalities. Because of that, the impacts of climate change and urbanization will require collaborative solutions (CWCB, 2023).

With this many challenges and changes in weather, green roofs are an impactful, nature-based system to be added on a large scale in this area. However, generalizing green roofs can result in mismatched expectations because the benefits of a particular project depend on many variables. Few standards for design details and materials exist in North America, and most projects are not monitored. Project data performance prediction is difficult, even more in such diversified climate conditions (McIntyre & Snodgrass, 2010). Despite the lack of data in North America, many cities already validated its importance and use green roofs for policies and incentives.

3.7 Denver Area Water Law and Green Roofs

In many cities in the United States and worldwide, it is possible to apply water reuse and water storage policies to solve problems related to water scarcity and stormwater management issues. However, Colorado water law is not aligned with those technologies in this way. The "first in time, first in right" basis of Colorado water law says that people who were first to file for water rights obtained senior rights. Those who filed afterward obtained junior rights and could not divert water until senior rights were fully satisfied (Denver Water, 2022).

Colorado's water rights can limit what is practical for stormwater harvesting. In the western U.S., stormwater capture and use may influence downstream water rights dependent on that runoff. In Colorado, for example, it is only since 2016 that rainwater from rooftop gutters was allowed for non-potable outdoor uses, and only with rain barrels with a combined capacity of 110 gallons. However, on average, 10,434,000 acre-feet of water leaves the state each year (one acre-foot equals 43,560 cubic feet, or 325,851 gallons, of water, which can serve the needs of two families of four to five people for one year). About 80 percent of the water in Colorado drains from the Western Slope, which has led to the Front Range moving water from the Western Slope to the Eastern Slope through trans-basin diversions. Approximately 475,000 acre-feet of water from the Colorado River basin is transferred to the Eastern Slope each year. On average, Denver Water customers use about 125,000 acre-feet of Western Slope water annually (Denver Water, 2022).

3.8 Green Roof Policy Examples

Urban stormwater harvesting can help cities reduce dependence on imported water or unsustainable groundwater withdrawals, improving the quality and quantity of runoff water. In this case, stormwater harvesting use will help diversify city water supplies, not just as a flood control problem but also as an opportunity for water supply and greening semi-arid urban areas (Luthy et al., 2019). Furthermore, a green city project aims to combine water management with green infrastructure, focusing on recreating a naturally oriented water cycle. In this way, green roofs have emerged as a great strategy and multifunctional component to reduce runoff, storing rainwater in leaves, substrate, and lower layers, and helping to restore urban ecology (Hoang & Fenner, 2014).

During a cost-benefit analysis for green roofs in development, Niu et al. (2010) presented the case of Vancouver and said that benefits related to stormwater management are the most significant. With the range from US$3.4M to US$4.1M a year, the infrastructure benefits are related to water quality improvements, reduction in stormwater runoff, lowering risks due to climate change, reducing stormwater impact in aquatic life, and finally, benefits related to stream erosion. On top of that, they say that green roofs in Vancouver can be Net Present Value (NPV)-positive in six years, mainly because of their air pollution mitigation and stormwater benefits, when compared to conventional roofs over the lifetime of 40 years.

The City of Toronto incurred annual cost savings of C$79,000,000 and C$14,000,000 in pollution control with the widespread implementation of green roofs. In Portland, Oregon, green roofs, among other technologies, are helping the city to solve a US$ 1 billion CSO problem (Green Roofs for Healthy Cities, 2013). In 2013, around 42 million gallons of stormwater were captured in Cincinnati, Ohio, with the benefits from this program. They installed 163,873 square feet of green roofs due to the initiative of the Green Roof Loan Program (Project Groundwork, 2013).

Seattle created requirements designed to increase the quantity and quality of planted urban areas to meet development standards, like the Seattle Green Factor established in Seattle Municipal Code. This applies to new development in commercial and multifamily residential zones outside of downtown. Green roofs are included as a Green Factor compliance, and bonus credits are available for native plants, drought tolerance, and food cultivation on green roofs. Besides Seattle's Green Factor, there is also the Built Green Certification and SPU's updated Stormwater Code, which incentivizes green roofs in more retrofits and new development (McIntosh, 2010).

Philadelphia is another domestic example that validated the importance stormwater management of green roofs, creating incentives for their implementation. They have the Green Roof Tax Credit, there is a credit provided to reward the construction of a roof that supports living vegetation. Starting in 2016, the credit to be claimed is 50% of all costs incurred to construct the green roof; however, not to exceed $100,000 (City of Philadelphia, 2023).

Moreover, in November 2017, a green roof initiative was passed in Denver, Colorado. This required new and existing buildings over 25,000 square feet in size to install a green roof. The ordinance aimed to achieve important environmental benefits for the city, like reducing urban heat island impacts and greenhouse gas emissions. However, in its initial version, the green roofs ordinance had several limitations, including legal challenges surrounding rainwater retention, the inability of many existing buildings to support the weight of a green roof, and high construction costs. In 2018, the Green Building Requirements were modified, and cool roofs were added, roofs that contain a minimum solar reflectance (City and County of Denver, 2021[b]). These types of rules and regulations limit the incentive and the use of such a beneficial tool for the development of a better living city.

The investments and payoff from green roof technologies benefits the city and can be calculated from savings from avoided stormwater-related costs, such as stormwater equipment downsizing, reduced stormwater maintenance and stormwater fee (Sproul et al 2014).

3.9 Importance of simulation events

Colorado's rain distribution pattern and volume of rain can pose a challenge when collecting stormwater data due to its availability and distribution. The idea of performing simulation rainfall events is essential to represent the green roof's full capacity of retaining and detaining rainfall in different rain sizes and intensities in Colorado Front Range.

To determine storage volumes, runoff coefficient, and other factors that evaluate the efficiency and design of a controlled experiment, such as the green roofs in this study, it is recommended to perform testing of green stormwater infrastructure (GSI). The Philadelphia Water Department (2009) indicates the importance of simulation events to verify that water flows through the project as designed and to measure the infiltration rate of constructed slow-release systems.

The GSI performance testing described by Philadelphia Water Department (2009) applies to different GSI Stormwater Management Practices (SMPs). It recommends the Subsurface Infiltration Rates, calculated by simulated runoff testing, to measure water's lateral and vertical movement as the storage volume over time. It focuses on infiltration rate measures to help reduce runoff volume, minimizes natural rain processes, and increases soil absorbency, reducing flooding risks.

The simulation allows the project to cover all the magnitudes and confer to the project the most accurate scenario. The effective discharge is the one that transports most sediment on an annual basis, often characterized by the annual and the 5-year event. To improve channel stability and reduce erosion, it is important to simulate, on a full spectrum, the largest and the smaller events. A Water Quality Capture Volume (WQCV), described in the Mile High Flood District Criteria Manual, is used to evaluate the water quality and hydrological impacts of urbanization on receiving waters based on analyzing rainfall and runoff characteristics. It is 0.6 inches of precipitation, the 80th percentile storm event, and the overall percentile distribution of rainfall depths in the area (UDFDC, 2010).

The difference in climate and rain event sizes will determine the retention performance of the green roof for a specific location based on storm event size retention and annual retention. The factors controlling retention performance, such as substrate and structural detention layers, and the climate conditions for which green roofs provide optimal performance. Large design storms (i.e., storms with return periods greater than 2 years of stormwater management design) are assessed to evaluate green roof retention for large events (Sims et al., 2016).

The substrate moisture can be used to determine the effectiveness of runoff reduction during a rain event. The moisture of the substrate before a rain event can indicate better absorption or saturation, affecting the effectiveness of the green roof retention capacity.

The importance of understanding the potential of infiltration in each green roof system depends on the rain's intensity and will determine the retention and detention rate. Usually, when a rainfall event's intensity is smaller than the potential infiltration rate of the substrate and the layers underneath it, such as blue-green roof structures, all the precipitation events will be infiltrated through the substrate and be intercepted by the vegetation. However, when the intensity of a rainfall event is greater than the potential infiltration rate, overcoming the field capacity, the infiltration rate through the substrate equals the potential infiltration rate, leading to ponding rainwater on the surface of the substrate or instant runoff (She & Pang, 2010).

The ability to create particular rain events through rainfall simulation gives a range of analyses options and specificities for a project. It can vary by parameters of interest, such as foliar cover or soil type, and control event properties, such as intensity and duration (Dunkerley, 2008).

3.10 Products Specifications and Performance

The lack of research, data availability, and objective standards in North America can lead to a challenge for new green roof implementation. The relatively low percentage of green roofs installed makes some of the public benefits hard to measure effectively. However, the concern about environmental issues has increased the green roof industry and is increasingly catching the attention of designers, construction companies, horticulture, and landscaping industries (McIntyre & Snodgrass, 2010).

This constant increase in interest can help to grow the green roof industry. With more companies working on projects, the diversity of projects and costs should also vary. The long-term success of the industry depends on the availability of materials and components with consistent characteristics and performance validated in the field. And wide-ranging projects to produce the needed data and experience. Unfortunately, many green roofs still carry a wrong judgment due to insufficient expertise and ill-conceived designs (McIntyre & Snodgrass, 2010).

Some specific performance characteristics will be drawn in the early phases of green roof design. That's why it is so important to point out all the project expectations. The many benefits the green roof can provide requires different materials, layers, substrate depths, and vegetation variety.

Green roof guidelines and standards are important tools to better understand a green roof project and narrow down specificities from different designs and applications. U.S.-based ASTM International have established a green roof task force and published a series of testing methodologies and broad guidelines to discuss technical requirements such as plants, substrate, wind scour resistance, substrate reinforcement, separation or filter layers, drainage layers, water retention layers, protection layers, and root penetration barriers (ASTM International 2009). In this guide, it is possible to identify terminology, principles, and fundamental concepts, including those related to sustainability, technical requirements of construction, and types of green roof systems (ASTM, 2020). Better tools to measure the performance of different materials will make the green roof specification process and installation clearer and easier to understand (McIntyre & Snodgrass, 2010).

Green roofs' economic analyses usually don't include all benefits due to lack of accurate measurement. In a research review, Manso et al. (2021) analyze the benefits and costs of different types of green roofs, divided between building scale benefits, urban scale benefits, and life cycle costs. The authors point out that there are hardly any data regarding intangible benefits, such as the promotion of quality of life and well-being. And the high variability in available data is mostly related to the different characteristics of the systems, the building's structure, the surrounding environment, and local weather conditions.

Compared to conventional black and white roofs (Sproul et al., 2014), green roofs can be more expensive and require extra maintenance depending on the vegetation type and irrigation needs. Depending on some characteristics and complexities, such as the substrate thickness, some buildings may need an increased weight load capacity of the roof to be able to be implemented (Manso et al., 2021). The price varies, but an average installation of an extensive green roof can is about US$11 per square foot. An intensive green roof is about US$38 per square foot. Or US$112 per square meter for an extensive green roof, and US$409 per square meter for an intensive system (Manso et al., 2021). The weight also depends on the project intentions, but a standard 10 cm deep *Sedum* roof has a saturated weight of about 80 kg/m² (Sempergreen, 2023).

The available space and buildings with the capacity for retrofitting can limit the implementation of green infrastructure. However, the benefits from multifunctional solutions and integrating green infrastructure into the existing urban landscape make green roofs an attractive solution (Busker, 2022).The creation of standards and guidelines for North America, combined with long-term research and data available to the public, will help governments to establish policies and incentives which can solve some municipal problems, such as water quality impairments from stormwater runoff. The incentives are the door opener to make green roofs more economically feasible to install. In addition, detailed quantification of benefits will make a stronger argument to building owners that green roofs are a safe, functional, and compatible building addition (McIntyre & Snodgrass, 2010).

4. Materials & Methods

To achieve the goals outlined for this project and potential green roofs benefits analyses, a control roof and three different green roofs technologies were placed in CSU Horticulture Center at 1707 Centre Ave in Fort Collins (Figure 4. 1); the three systems include a Sponge Roof, a Purple Roof, and a green roof technology with Extenduct drainage system, all vegetated with Sedum mats, which are predominately low growing, succulent, evergreen species. All the systems have the same substrate, LiteTop Intensive Media blend provided by American Hydrotech, Inc (Chicago, IL, USA).

Figure 4. 1 - Location of the study with Google Earth.

To assemble the system, four wood boxes were built (Figure 4. 2) with a PVC waterproof membrane (Figure 4. 3), which was donated by Andy Creath of Green Roofs of Colorado. Each box was secured on top of three sawhorses and leveled on a 0% slope (Figure 4. 4).

The survivability of vegetation, type of green roof layers, substrate moisture content/dry-down, and drainage rate efficiency were monitored. Each green roof technology has a drainage system, measuring the runoff water and its delay (runoff reduction), draining to individual outlets. All three green roofs have an individual runoff flow measurer, Leveloggers (model, manufacturer, manufacturer location). Data from outflow water was downloaded onto a computer and compiled after each natural and simulation rain event develop hydrographs (rate flow over time). This allows us to compare the three green roof systems and determine their runoff coefficient.

Figure 4. 2 – Wood Box

Figure 4. 3 – PVC Membrane

Figure 4. 4 – Wood Boxes level on Sawhorses

4.1 Control Roof System

The control roof is a wooden box with a waterproof membrane layer, the same materials (PVC membrane) and dimensions as the green roof systems (1 m x 2 m) (Figure 4. 5). This system compares runoff from a conventional low slope roof with green roof systems during rain events.

Figure 4. 5 – View of Control Roof

4.2 Green Roof System with Extenduct drainage/water retention layer.

The Extenduct green roof system (Figure 4. 6) is a 1 m x 2 m green roof system with a 20-mil root barrier constructed of virgin polyethylene with a carbon black additive, with no plasticizers. The Extenduct drainage/water retention layer is a 40% recycled drainage core in a waffle pattern with a geocomposite fabric bonded to the top side was supplied by Green Roof Solutions (Glenview, Illinois, USA).

In this system, the drain was sealed with waterproof tape at the waterproof membrane level. The Extenduct drainage/water retention layer (Figure 4. 7) is placed between the waterproof membrane and the substrate, working as a water retention layer and a filter membrane. The substrate is the LiteTop Intensive blend by American Hydrotech, with 15 cm of depth (Figure 4. 8). Sedum tiles were used as vegetation (Figure 4. 9).

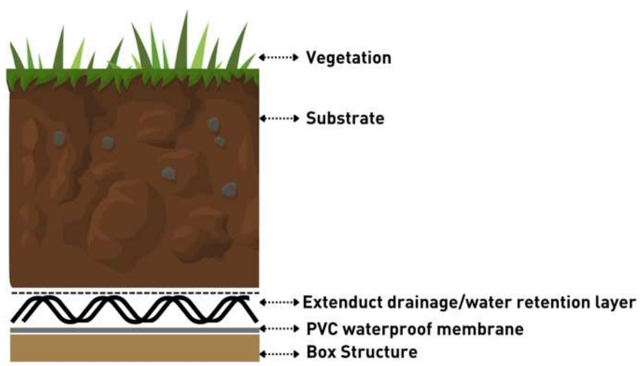

Figure 4. 6- Green Roof system with Extenduct drainage/water retention layer

Figure 4. 7- Drain and Extenduct membrane.

Figure 4. 8 - LiteTop Intensive blend by American Hydrotech

Figure 4. 9 – Vegetation - Sedum tiles

4.3 Sponge Roof System

The sponge roof system (Figure 4. 10), supplied by Sempergreen (Culpepper, Virginia, USA), is a green roof technology with a detention layer and needled mineral wool to promote an increase in water detention and evapotranspiration in the system. The detention layer is a 5mm thick detention layer fabric made from polyester. This layer breaks up a laminar flow, increasing turbulence and friction, pushing the water to the overlaying layer, the needled mineral wool, which is a lightweight layer, high-retention green roof technology that instantly absorbs the inflow water and easily gives the water back to the plants, by passive irrigation.

In this system's assembly, the drain was sealed with waterproof tape at the waterproof membrane and level with the detention layer under the needled mineral wool retention layer in order to store more water (Figure 4. 11). On top of those layers, 15 cm of substrate (LiteTop Intensive blend by American Hydrotech) (Figure 4. 12) and vegetation (sedum tiles) (Figure 4. 13). This green roof has an area of 2 square meters (1mx2m).

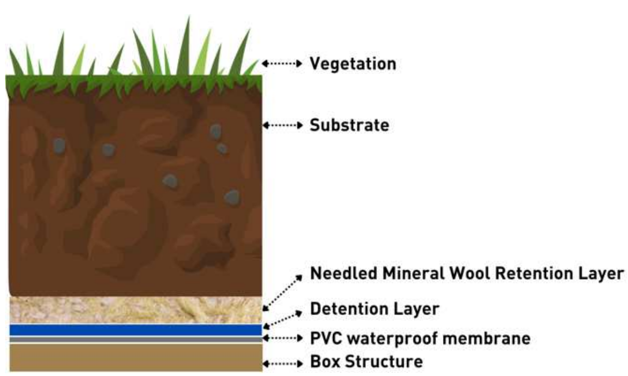

Figure 4. 10 - Sempregreen Sponge Roof system.

Figure 4. 11 - Drain and needled mineral wool retention layer

Figure 4. 12 - LiteTop Intensive blend by American Hydrotech

Figure 4. 13 - Vegetation - Sedum tiles

4.4 Purple Roof System

The purple roof system is supplied by Sempergreen (Culpepper, Virginia, USA). It is a 1 m x 2 m green roof (Figure 4. 14) with the same layers as Sponge Roof (Section 4.3); however, between the detention layer and the needled mineral wool retention layer, there is an 85 mm honeycomb detention reservoir, made from polypropylene. The Honeycomb detention reservoir has a honeycomb shape, with small diameter cylinders, vertically oriented, promoting temporary water storage (Figure 4. 15).

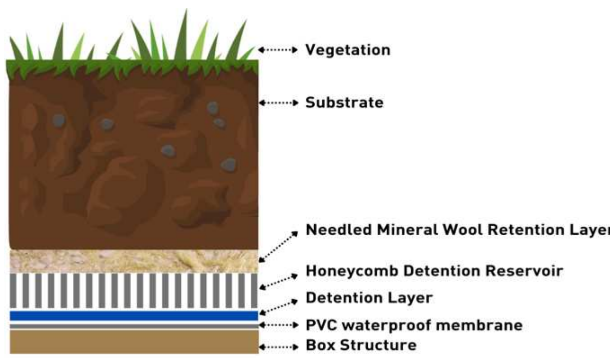

Figure 4. 14 - Sempergreen Purple Roof system

Figure 4. 15 – Purple Roof Layers – from top to bottom: needled mineral wool retention layer, honeycomb detention reservoir, and detention layer (detentionroof.com).

In this system, the drain was sealed with waterproof tape at the waterproof membrane, the detention layer was placed on top of it, and it was level with the honeycomb detention layer under the needled mineral wool retention layer (Figure 4. 16), helping to store more water. On top of those layers, a 15 cm of substrate (LiteTop Intensive blend by American Hydrotech) (Figure 4. 17) and vegetation (sedum tiles) (Figure 4.

18). When the water storage overflows, water not absorbed in the honeycomb detention layer is discharged from the system. Stored water is used by the plants as passive irrigation.

Figure 4. 16 - Drain level with detention and honeycomb layer – needled mineral wool retention layer on top

Figure 4. 17 - LiteTop Intensive blend by American Hydrotech

Figure 4. 18- Vegetation - Sedum tiles

4.5 Instrumentation

4.5.1 HOBO Weather Station

A HOBO weather station system was used to obtain the results and accurately compare the three green roof technologies. The HOBO system (Model HOBO U30 USB Station [U30-NRC] Bourne, MA, USA) is used as a performance tool. This system collects data on ambient air temperature, relative humidity, dew point, wind direction, wind speed and gust, substrate temperature, and substrate moisture. The weather station is set up to sample data every minute. It is installed on the sides and sawhorses of the Control Roof System (Figure 4. 19). It collects essential data to establish irrigation frequency, runoff efficiency, vegetation health, and aesthetic purposes.

For monitoring stormwater runoff and determining the survivability of the vegetation, the roofs were monitored from June 16th, 2022, until May 19th, 2023. Stormwater runoff was monitored using Leveloggers (Levelogger 5, Model 3001, Georgetown, Ontario, Canada) and a Barologger (Barologger 5, Model 3001, Georgetown, Ontario, Canada).

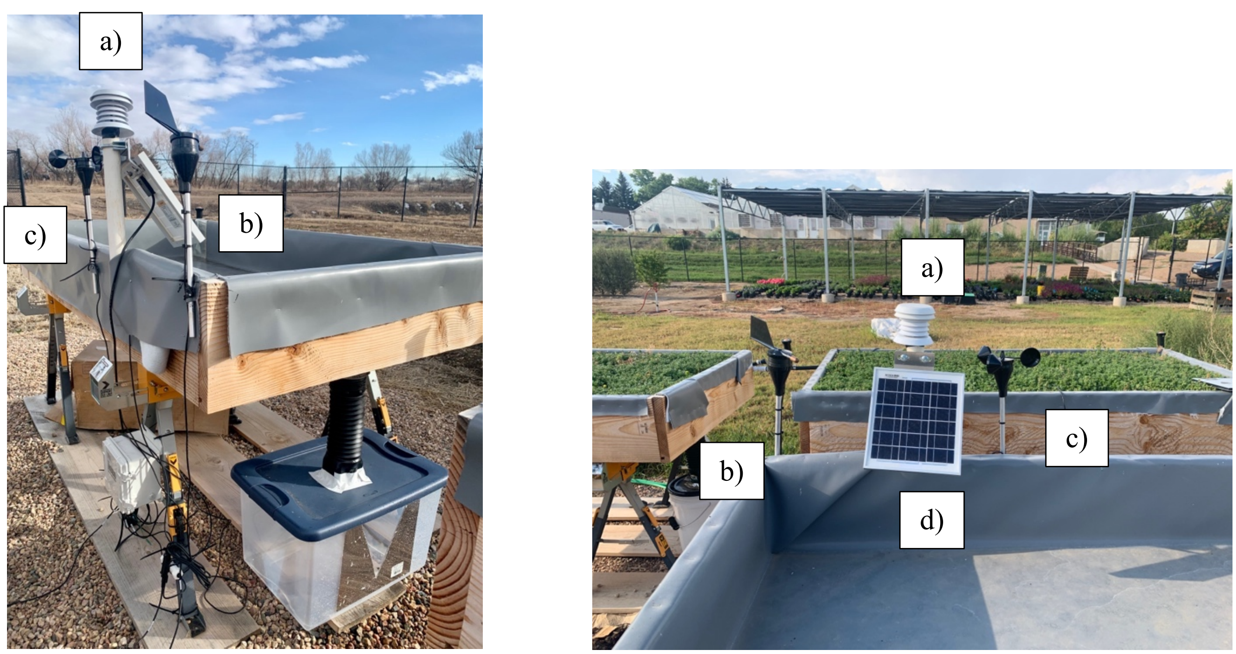

Figure 4. 19 - HOBO Weather Station U30-NRC. a) Temperature and Relative Humidity Sensors. b) Wind Direction Smart Sensor (S-WDA-M003). c) Wind Speed Smart Sensor (S-WSB-M003). d) 5-Watt Solar Panel (SOLAR-5W).

4.5.2 Substrate Temperature

The variation in temperature in the Front Range area during the year is vast, with hot summers and cold winters, which can directly affect substrate properties. With that, to accomplish the objectives of this study, mainly under freezing conditions, temperature sensors from HOBO were installed in each green roof system, 10 cm (4 inches) below the vegetation layer (Figure 4. 20), and configured to measure data every minute. The smart temperature sensors, the Onset 12-Bit Temperature Smart Sensor (S-TMB-M002), are used to measure the temperature of the soil and are designed to connect to the HOBO weather station.

From this data, it is possible to analyze the temperature of the soil before a natural rain event, snow, and rain simulation events and determine the conditions of the soil, frozen or thawed. It analyzes how the temperature can impact the system, considering its size, intensity, duration, and the previous temperature inside the system. With that, it can indicate some flooding conditions inside the green roof systems, if frozen, and the speed of outflow water. Furthermore, the sensors' data inside the systems offer a comparison in terms of thermal resistance with the outside temperature data.

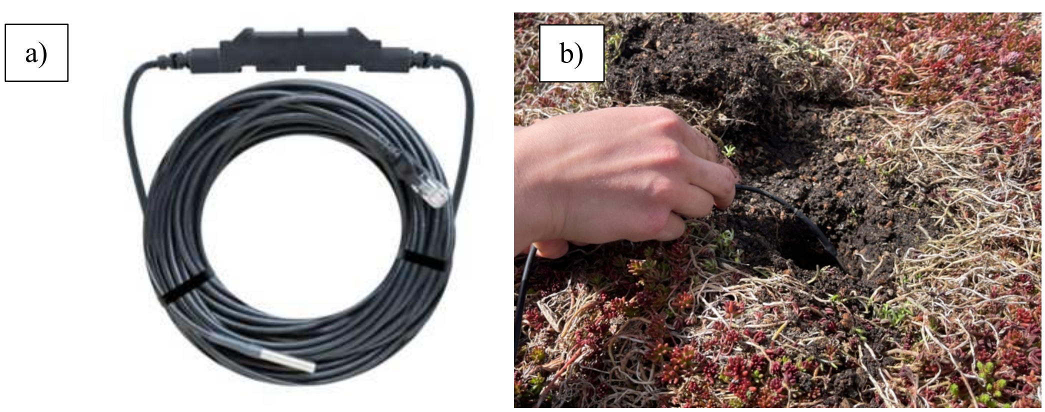

Figure 4. 20 a) Onset 12-Bit Temperature Smart Sensor (S-TMB-M002). b) Onset 12-Bit Temperature Smart Sensor being installed on the green roof system.

4.5.3 Substrate Moisture

To accomplish the objectives of this study, HOBO soil moisture sensors were installed in each green roof system, 12 cm (5 inches) below the vegetation layer (Figure 4. 21). The soil moisture smart sensors, the Onset soil moisture sensor probe (S-SMC-M005), are used to measure substrate water content and are designed to connect to the HOBO weather station.

The Onset soil moisture sensor probe measures the water content in the space immediately adjacent to the probe surface. Special care was taken when installing them, ensuring no air gaps or excessive soil compaction around the probe, which can profoundly influence soil water content readings.

Onset soil moisture sensor probes provide ±3% accuracy in typical soil conditions and ±2% with soil-specific calibration. They measure the dielectric constant of soil to determine its volumetric water content. Readings are provided directly in volumetric water content. All sensor conversion parameters are stored inside the smart sensor adapter, so data is provided directly in soil moisture units.

To analyze its reading during operation, Onset's HOBO and InTemp Data Loggers (2022) consider values of 0 to 0.5 m3/m3 possible. Also, a value of 0 to 0.1 m3/m3 indicates oven-dry to dry soil respectively. A value of 0.3 or higher normally indicates wet to saturated soil.

It was taken special care of sudden changes in value because this can typically indicate that the soil has settled or shifted, which are signs that the sensor may not be installed properly or that it has been altered or adjusted during deployment. In this case, the soil moisture sensor was removed and rearranged in the substrate. If the error continued, the soil moisture sensor was replaced with a new one.

From this data, it is possible to analyze the volume of water on the substrate before rain simulation events and determine when it is best to do it. It analyzes how the rain event impacted the system, considering its size, intensity, duration, and the previous volume of water inside the system, as it occurs when subsequent rain events happen. Furthermore, it indicates the best time to irrigate the system, to supply the best conditions for the vegetation.

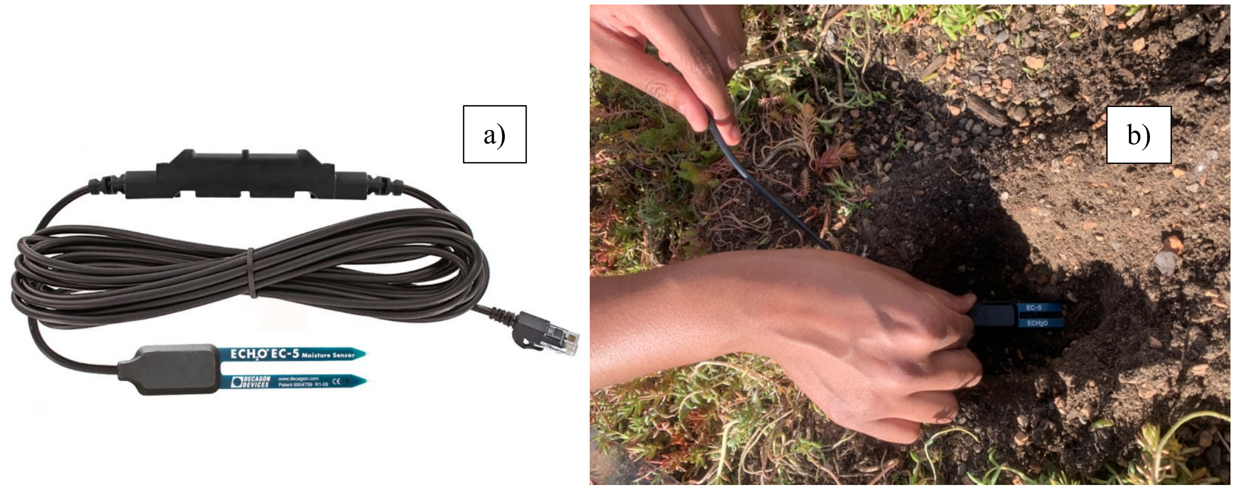

Figure 4. 21 a) Onset Soil Moisture Sensor with 5 cm Probe (S-SMC-M005). b) Onset Soil Moisture Sensor being installed on the green roof system.

4.5.4 Substrate Soil Moisture Calibration

The soil moisture sensors used in this project, to comply with the objectives, the onset soil moisture sensor probe (S-SMC-M005), comes pre-calibrated for most soil types. Those probes measure the soil's volumetric water content by measuring the soil's dielectric constant, which is a strong function of water content. However, not all soils have identical electrical properties. Green roof substrate has unique water-holding characteristics. Due to variations in soil bulk density, mineralogy, texture, and salinity, the generic mineral calibration for current sensors results in approximately ± 3-4% accuracy for most mineral soils and around ± 5% for soilless growth substrates (potting soil, rock wool, cocus, etc.). However, with soil-specific calibration, accuracy increases to ± 1-2% for all soils and soilless substrates. In this case, it is recommended to conduct a soil-specific calibration for the best possible accuracy in volumetric water content measurements (Cobos, 2009).

For the soil moisture calibration, it was done following the instructions by Cobos (2009). A sample of LiteTop Intensive substrate from Hydrotech was collected, the same substrate used in the three green roof systems and dried in a drying oven at 70˚C for at least 72 hours (Figure 4. 22).

Figure 4. 22 – LiteTop substrate inside drying oven.

Three replicates of 250 ml from the dried sample were separated for calibration (Figure 4. 23), named HC1, HC2, and HC3. The size of the sample pots was sufficient to submerge the sensor. In this experiment, the sensor used for calibration purposes was HH2 Moisture Meter from Delta-T soil moisture sensors (Cambridge, UK; Figure 4. 24).

Figure 4. 23 – Three LiteTop substrate samples.

Figure 4. 24 – HH2 Moisture Meter

All three samples received the same amount of water, starting with 25 ml until 150 ml, where the substrate was completely saturated. Table 4 1 shows the soil moisture reading in each sample and the dry (oven dry weight) and wet (substrate sample plus 150 mL of water) weight. With these results, it was possible to build a soil-specific calibration curve (Figure 4. 25).

Table 4 1 – Soil moisture readings from HH2 Moisture Meter.

	25 mL	50 mL	75 mL	100 mL	125 mL	150 mL	dry (g)	wet (g)
HC 1	5.70	15.40	20.60	30.20	36.00	40.10	273.87	371.66
HC 2	5.20	15.40	21.70	28.70	34.20	38.70	274.84	366.03
HC 3	6.40	10.80	21.00	28.40	35.40	39.60	276.48	371.16

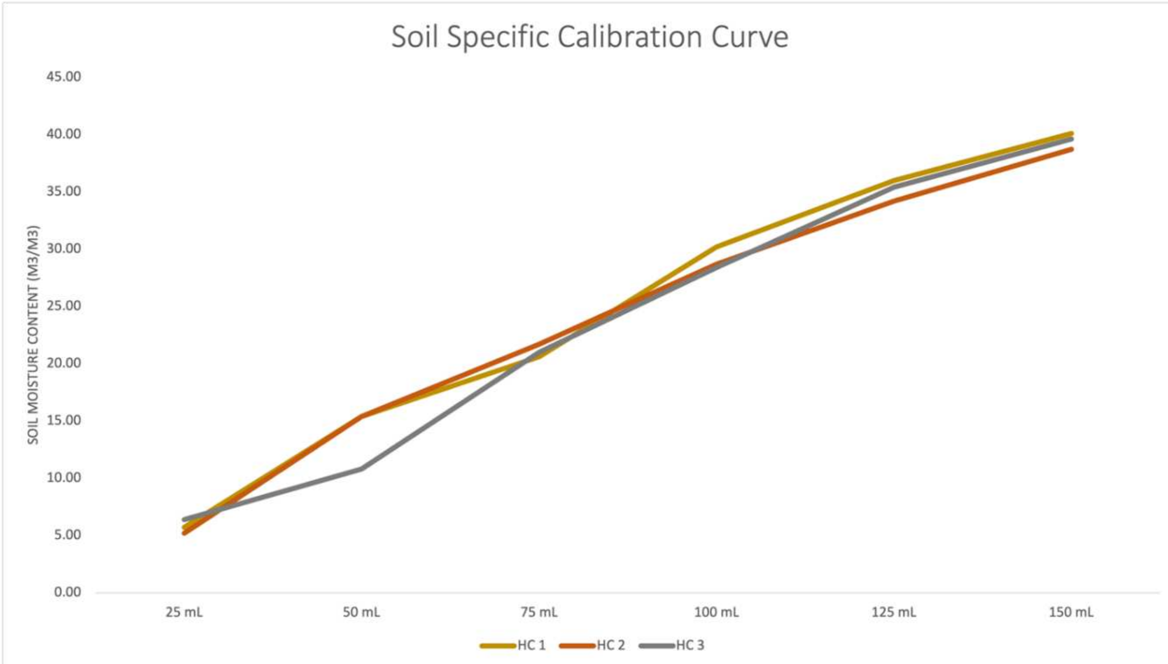

Figure 4. 25 – Soil Specific Calibration Curve

After the readings and validation with the HH2 Moisture Meter, the equipment was brought to CSU Horticulture Center (Figure 4. 26), where it was possible to measure each green roof system substrate and compare it with the onset soil moisture sensor probe (S-SMC-M005), as it is shown on Table 4 2. Which validated the accuracy of the HOBO soil moisture sensors installed in the green roof systems.

Table 4 2 Comparison between HH2 Moisture Meter and HOBO Soil Moisture Sensor readings.

	Extenduct Roof	Sponge Roof	Purple Roof
HH2 Moisture Meter	19.1	23	18.2
HOBO Soil Moisture Sensor	20.4	20	17.3


Figure 4. 26 – HH2 Moisture Meter at CSU Horticulture Center, reading soil moisture from a green roof system.

4.5.5 Weather Stations

Rain gauges are an essential tool to measure the intensity and duration of a rain event. This is used as important data for this research to see how the three green roofs and the control roof behaved during a rain event in terms of retention of water, reduction of runoff, and substrate moisture holding capability.

Due to the uncertainty and malfunction of the rain gauge in the location from May 2022 to June 2022, it was necessary to reach out to alternative weather stations close to the area to collect data on precipitation and relative humidity, and for the winter, snow. Although at the end of June 2022, a new weather station was placed at CSU Horticulture Center, the alternative weather stations were still used to compare and create better data.

The rain gauge (WH5360, Ecowitt, Shenzhen, China) installed at the end of June 2022 (Colorado State University Horticulture Center Rain Gauge) measures rain precipitation with 0.1mm/0.01-inch resolution, indoor temperature, and relative humidity (Figure 4. 27). Which allows the comparison of this data and the HOBO weather station.

Figure 4. 27 – Rain Gauge at CSU Horticulture Center

The weather stations were CoAgMET, located on Colorado State University's main campus (approximately 1.5 kilometers (1 mile) from the Horticulture Center), which collects data every 5 minutes and hourly on precipitation, air temperature, solar radiation, wind speed, and reference evapotranspiration. CoCoRaHS, which collect, and reports data to NOAA's National Weather Service, is used for daily precipitation data, including snow, and is located approximately 250 meters (0.2 miles) from the Horticulture Center. Also, Northern Water's weather station collects daily and hourly data on precipitation, air temperature, solar radiation, wind speed, and reference evapotranspiration calculations; it is located approximately 1.5 kilometers (1 mile) from the Horticulture Center (Figure 4. 28).

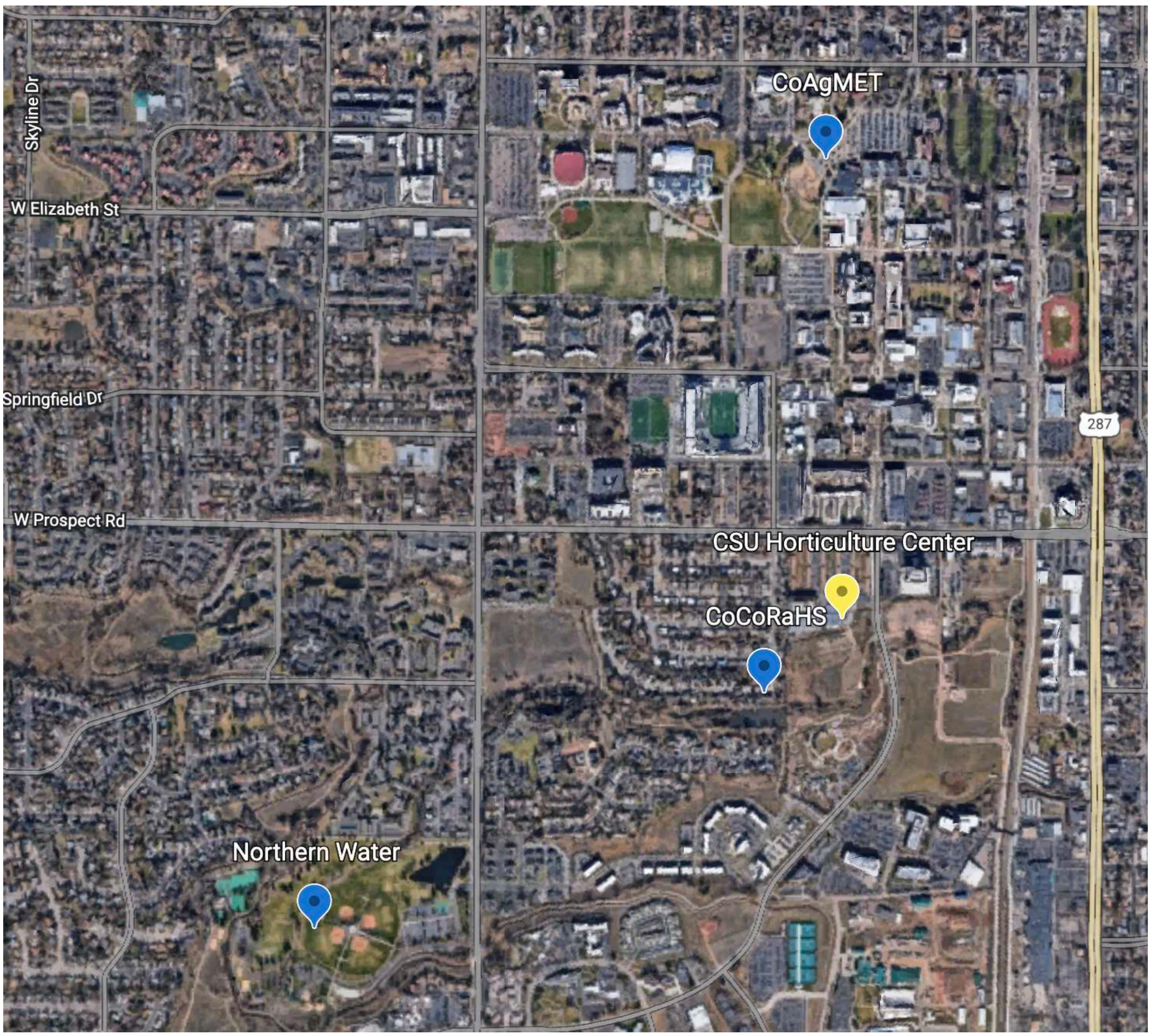

Figure 4. 28 – Picture from Google Earth exhibiting CSU Horticulture Center in yellow and the three weather stations, CoAgMET, CoCoRaHS and Northern Water, in blue.

4.5.6 Outflow Measurements

The outflow measurement system is designed to simulate the hydrologic performance of green roofs under variable precipitation conditions. The drainage systems in each green roof were designed to test performance under steady, low-intensity, high-intensity, short-duration, and long-duration rainfall conditions. Volume, speed, and time were measured to quantify the runoff from the green roof systems. All the systems have the same drain system; it consists of a 7.6 cm (3 inch) diameter drain connected to the weir under each structure. Inside the weirs are a Levelogger, four in total, and one Barologger (Figure 4. 29).

To measure the time and volume of water outflowed from each system, the Leveloggers give the absolute pressure (water pressure + atmospheric pressure) expressed in meters, furthermore converted in liters. The Barologger records atmospheric pressure in psi. The most accurate method of obtaining changes in water level is to compensate for atmospheric pressure fluctuations using a Barologger, avoiding a time lag in the compensation (Solinst Canada Ltd., 2022). The Barologger is set above the high-water level in one location on site, in this case, outside the control roof weir (Figure 4. 29 (E)).

To generate the compensated data, the Levelogger Software Data Compensation Wizard automatically produces compensated data files using the synchronized data files from the Barologger and Leveloggers on site. The Barologger uses pressure algorithms based on air rather than water pressure for more accuracy (Solinst Canada Ltd., 2022).

As the data is downloaded to the computer and compensated, it is possible to know the water level. In this case, calculate it from the volume of the outflow water and the time it took to generate the runoff. Making it possible to compare which green roof system retained more water inside the system, and the speed of its outflow water, also comparing the runoff in each system.

Each weir holds 14 L of water before it reaches the bottom part of the v-notches. However, before it reaches the v-notch, we can calculate the total volume of water by Equation 1. H and t were measured throught the Levelogger.

$$Equation\ 1: Q = AHt.$$

Where A is the area, length times width, H is the height of the water registered by the Levelogger, and t is the time the water took to reach that height.

Equation 2 represents a free-flowing V-notch weir's discharge (head vs. flow rate) equation. After the water reaches the v-notch.

$$Equation\ 2: Q = KH^{2,5}.$$

Where Q is the flow rate, H is the head on the weir, and K is a constant, dependent on the angle of the v-notch and units of measurement. In this case, K for a 45-angle degree v-notch with a head in meters is 571.4 (Isco, 2016).

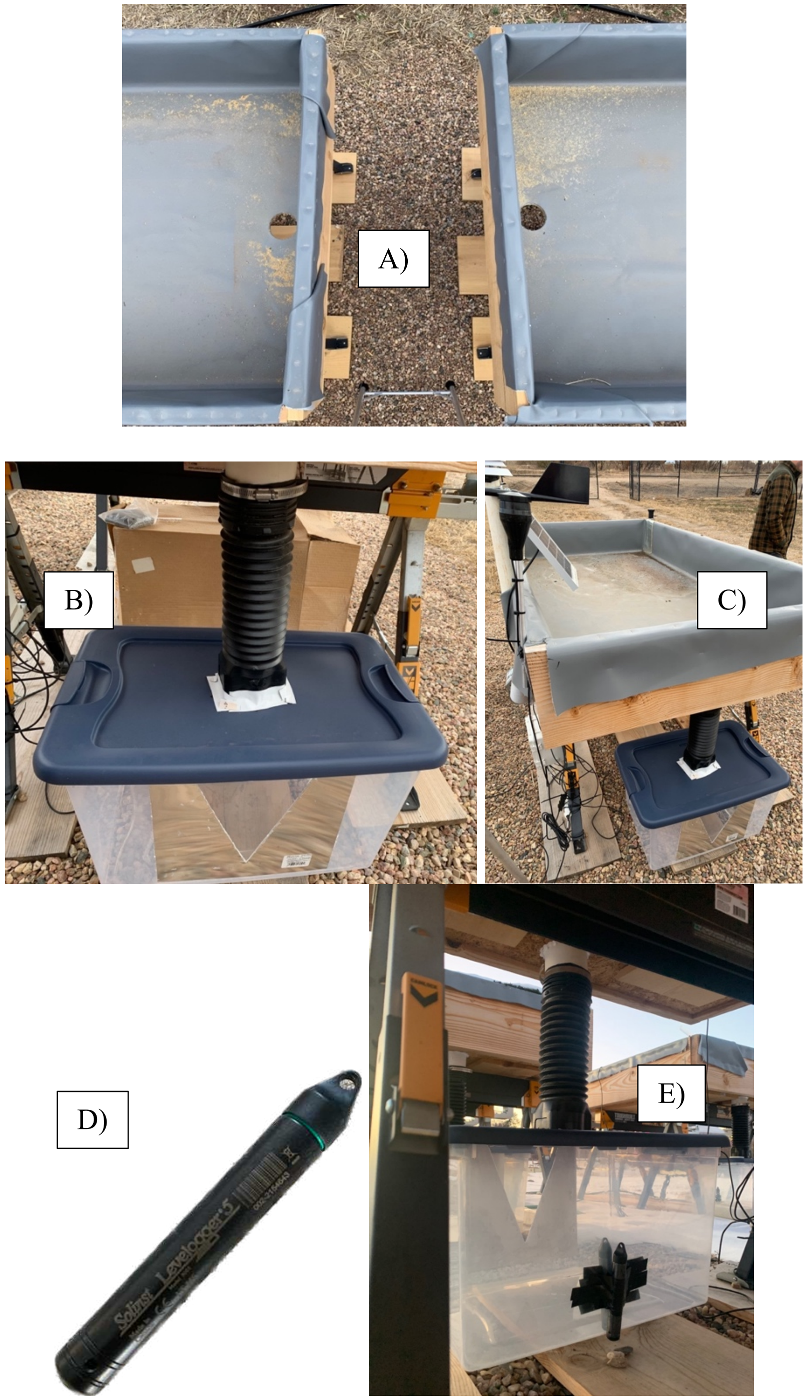

Figure 4. 29 - Outflow Measurement System. A) top view of the 3 inches orifice. B) Drains connected to the weir. C) View of the control roof system connected to the v-notch weir. D) Levelogger. E) View of Levelogger (inside the weir) and Barologger (outside the weir).

To calibrate the data, a simulation of a specific volume was made in a timed period. Using a flowmeter to measure the amount of water coming from the hose connected to it, 94 liters of water were poured inside the weir for 19 minutes (Figure 4. 30).

Figure 4. 30 – V-notch weir calibration test.

The Levelogger registered the water level inside the weir (Figure 4. 31). Using Equation 1 and Equation 2, it was possible to calculate 94 L passing thru the weir and v-notch in the same time interval, 19 minutes. Validating in this way the accuracy of the systems and equations to measure outflow water from natural and simulated rain events.

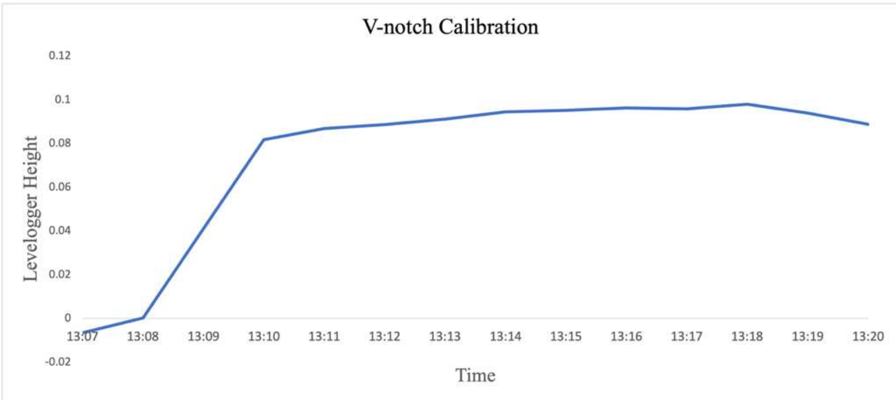

Figure 4. 31– Levelogger measure during calibration event.

4.6 Rainfall Simulation

Colorado's topography configuration, high elevation, midlatitude, and continental interior geography results in a cool and dry climate. This can be a challenge related to stormwater management data collection due to the lack of rainfall events in the area. Because of that, simulated runoff testing (SRT) 50-year stormwater events in Denver, Colorado, and a Water Quality Capture Volume (WQCV) event were performed to understand better volume retention, runoff coefficient infiltration rates, and substrate moisture retention in each green roof system.

Rain event properties such as duration and intensity may influence water partitioning among interception, evaporation, infiltration, ponding, and overland flow. Also exert a fundamental control on water-driven erosion processes such as splash, sheet flow, and rill flow (Dunkerley, 2008). However, those concerns are not applied in this experiment. The quality of the outflow water is not a subject of study, and the intensity of the water is not strong enough to disturb the systems, less than 10 liters per minute.

Sims et al. (2016) argue that the best indicator of water retention in any climate is the antecedent moisture content. So, the substrate moisture content in each green roof was analyzed for the simulated runoff testing. Ideally, the substrate moisture content should be less than 0.11 m^3/m^3.

For the measurements, a flowmeter was used to quantify the exact amount of water discharged into each green roof system (Figure 4. 32). Moreover, the size of each event was based on NOAA Atlas 14 Volume 8, which contains precipitation frequency estimates for selected durations and frequencies with 90% confidence intervals and supplementary information on the temporal distribution of heavy precipitation, analysis of seasonality and trends in annual maximum series data, for eleven midwestern states including Colorado. For this project, it was used a 60-minute recurrence interval depth. In this case, for each green roof were used 126 liters for the 50-year event, and 30.5 liters for the WQCV simulations. However, it was determined that an interval of time (1 hour) was not important in this kind of experiment, but the amount of water was. In other words, the precision of applying the specific amount of water to the systems was the focus (Figure 4. 33).

Figure 4. 32- Flowmeter used to quantify the amount of water used on the simulated runoff testing.

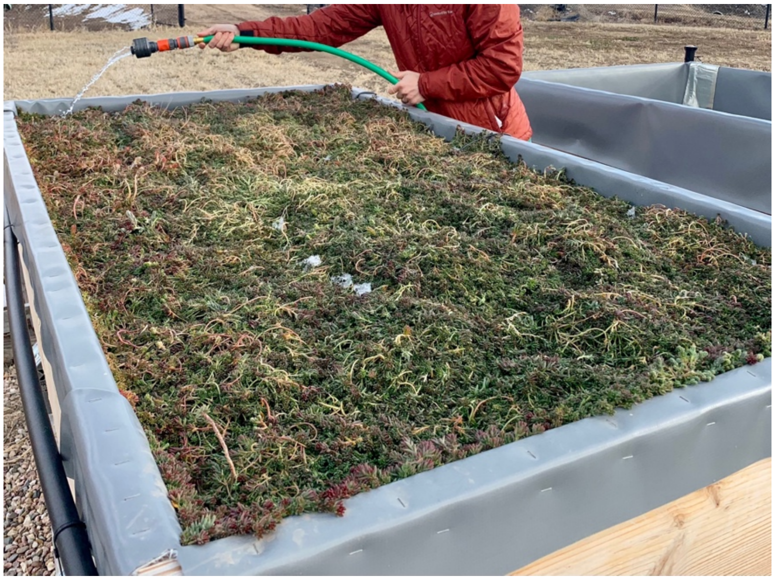

Figure 4. 33 – Simulation event on Extenduct Roof.

During each simulated runoff test, notes were taken about when the runoff started, when it reached the v-notch, and when the outflow speed decreased drastically. All are used to compare and properly read the Leveloggers data.

The simulated runoff testing was performed in different weather conditions to see how the green roof systems would respond. In total, 2 simulated runoff testing occurred in the winter of 2022 (11/15/2022) and spring of 2023 (04/08/2023).

4.7 Irrigation and Plant Health

The plant species used in all three green roofs, Extenduct Roof, Sponge Roof, and Purple Roof, are *Sedums*, which can tolerate various weather conditions. *Sedums* stay alive when most other plants perish; however, if moisture is not supplied to the system, plants go into drought response (McIntyre & Snodgrass, 2010). Plant health was evaluated over the entire planting season. An ex-post facto analysis was used to calculate the percentage cover using the large rectangular plot method (Bonham, 2013).

To avoid stress from planting, it was introduced irrigation for plant establishment. It used overhead sprinklers for irrigation from June to July 2022 (Figure 4. 34). To ensure the green roof systems had an equal volume distribution, five irrigation audits were run in total. Due to pressure and uneven distribution, cutting the hose, splitting the irrigation, and setting up a different time for each green roof were necessary. In this way, the green roofs could receive the same volume of water.

On July 22nd, 2022, the irrigation stopped because of some small rainfall events and simulation events that supplied the systems with enough moisture until October 14th,2022, when the substrate moisture content was low, demanding more irrigation. As a result, the green roofs were irrigated twice in October 2022, but not with the overhead sprinkler systems. For these two irrigations, it was used a flowmeter connected to the hose and irrigated by hand. Then, it was stopped again until the end of the project because precipitation and snow restarted.

Figure 4. 34 – Overhead sprinklers system for irrigation.

5. Results and Discussion

5.1 Quantitative Analysis of Runoff

The first objective of this research is to analyze the impact of water capture and, consequently, the reduction of runoff, retention volume, and runoff coefficient of the three green roof systems, a green roof with an Extenduct drainage/water retention layer, a sponge roof, and a purple roof, in Colorado's climate.

Quantifying the excess urban runoff volume (EURV) is possible to determine the difference in stormwater runoff volume on the pervious land surfaces, in this case, on the green roof systems, based on the storm runoff before and after the development. It has the idea of slowly releasing the water inside the system, decreasing the peak discharge, and working as a flood control detention tool (UDFCD, 2010).

5.1.1 Stormwater Management Analysis

For the runoff analysis, different rain event sizes were evaluated to analyze a variety of precipitation events that may occur in the Front Range area, such as natural rain events, and simulation of 50-year and Water Quality Capture Volume (WQCV) rain events. Including back-to-back analyses of the rainfall events.

For the natural and simulated rainfall events, the runoff delay was calculated, which is the difference from the time of the beginning of the rain event, until the start of runoff from the drain. The retention volume is the total volume of water inflow in the green roof systems minus its outflow volume. And the runoff coefficient is the runoff volume per total rain volume.

On November 15th, 2022, with an ambient air temperature of 3 degrees Celsius, a 50-year rain event was simulated. Using NOAA Atlas 14 Point Precipitation Frequency Estimates for Colorado, a 50-year design storm will be around 2.49 inches of precipitation or 63.25 mm in a 60-minute recurrence interval depth.

Converting this precipitation event size to the area of the green roofs, 2 m^2, it results in approximately 126 liters of inflow water for each system.

Using a flowmeter to measure the inflow of water, it took between 10 and 15 minutes, 11 or 8 liters per minute, to simulate the 50-year rainfall event. The runoff volume and substrate moisture content of each green roof system is presented (Figure 5. 1). Each of the green roof systems had an ideal substrate moisture content below 0.11 m^3/m^3. As represented by the line chart, the substrate moisture content for the Extenduct Roof was 0.0504 m^3/m^3, Sponge Roof was 0.0286 m^3/m^3, and Purple Roof was 0.1092 m^3/m^3. Even though the Purple Roof had the highest substrate moisture content, the difference was still very minimal as all the substrates were very dry.

The runoff volume (Figure 5. 1) is represented by the bar chart axis on the right side of the graph. Extenduct Roof and Sponge Roof runoff had the same runoff volumes, 38 liters, and volume retention of 88 liters each. Purple Roof had an outstanding volume retention of 119 liters, with 7 liters of runoff volume. The runoff coefficients were 0.06 for the purple roof and 0.3 for the Sponge Roof and Extenduct Roof.

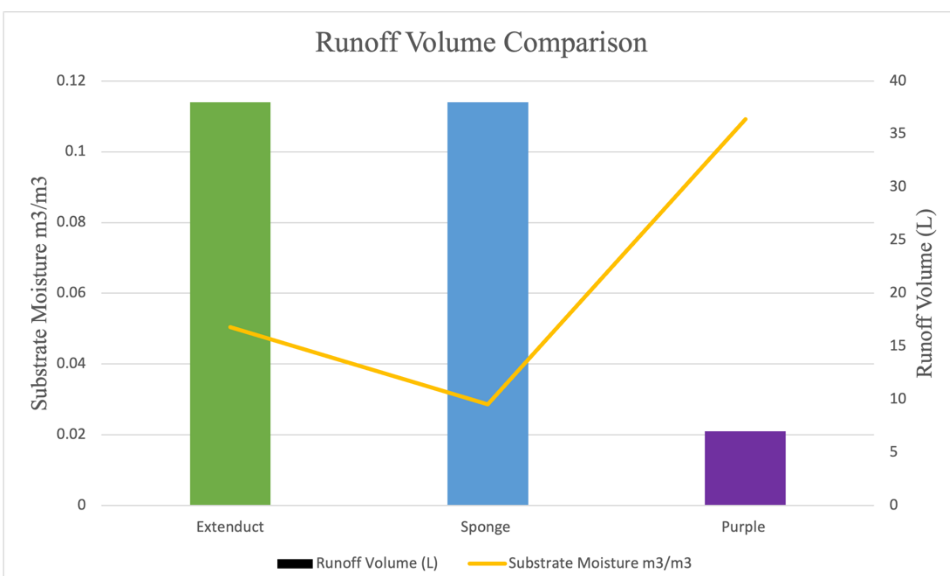

Figure 5. 1– Runoff Volume Comparison, substrate moisture content versus runoff volume, between Extenduct Roof, Sponge Roof, and Purple Roof on November 15, 2022, for the 50-year simulation.

The 50-year rain event simulation behavior of each green roof system is shown (Figure 5. 2, Figure 5. 3, Figure 5. 4). The Water Input (L/min) is shown on the right axis, with the bar chart, which represents the amount of inflow water per minute in each green roof system. The line chart represents the Flow Rate (L/min) which is the volume of runoff water per second.

The Extenduct Roof had a runoff delay of 4 minutes, taking 2 hours to stop the runoff (Figure 5. 2). While the Sponge Roof had a runoff delay of 8 minutes, taking 3 hours to stop the runoff (Figure 5. 3). Purple Roof had the greatest runoff delay, 12 minutes, with its runoff lasting 35 minutes (Figure 5. 4).

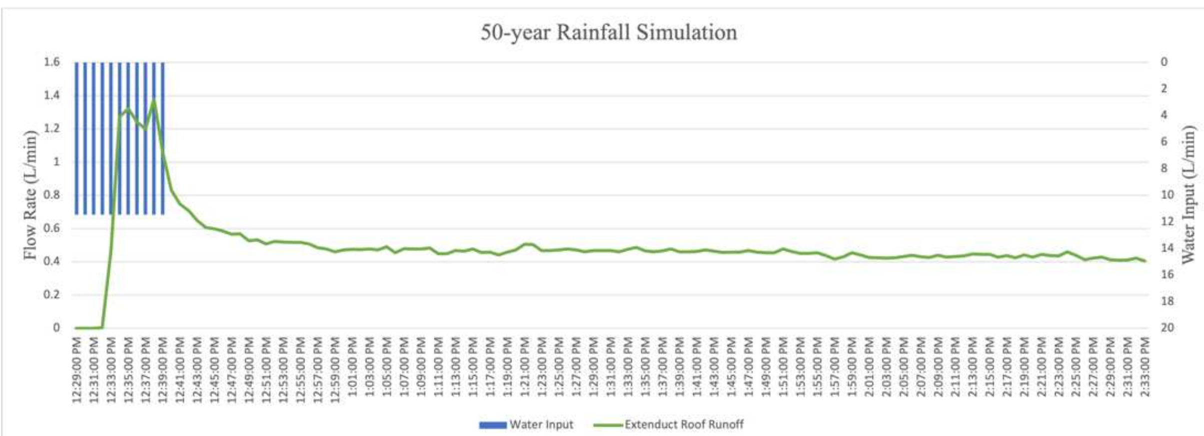

Figure 5. 2– 50-year rainfall event simulation event on the Extenduct Roof on November 15, 2022.

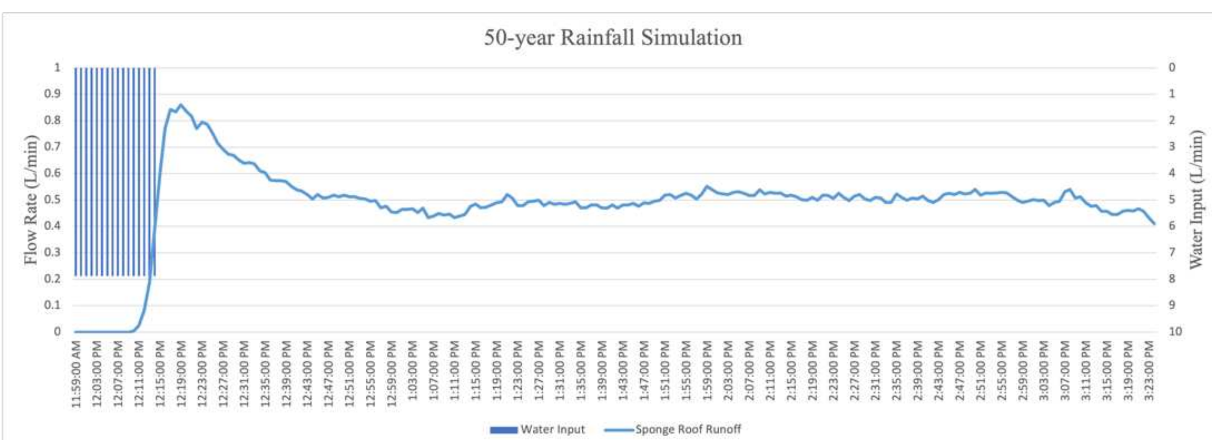

Figure 5. 3– 50-year rainfall event simulation event on the Sponge Roof on November 15, 2022.

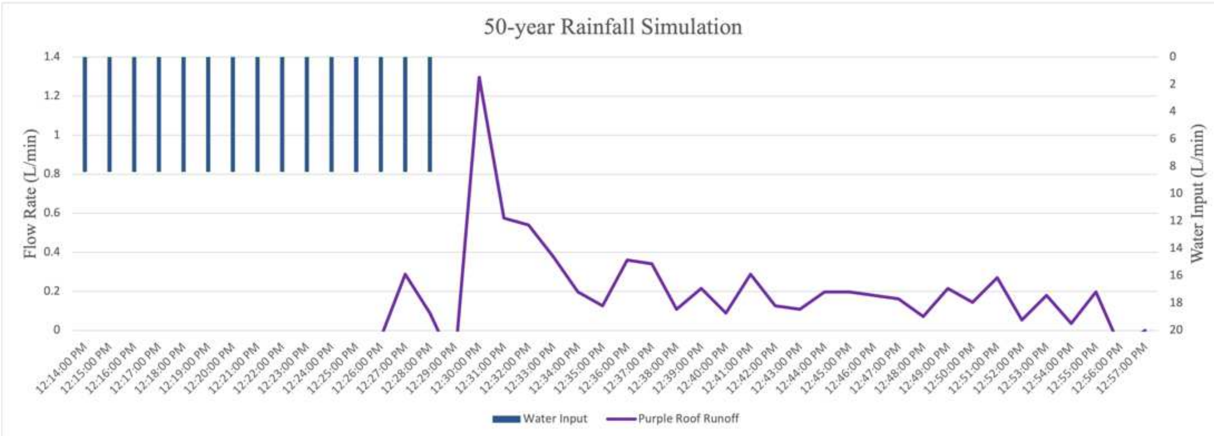

Figure 5. 4– 50-year rainfall event simulation event on the Purple Roof on November 15, 2022.

For the WQCV simulation, on April 7th, 2023, the substrate moisture content was higher than recommended in the literature review (Section 4.6), 0.11 m3/m3, due to a 4 inch snow event that happened 4 days before the simulation, on April 4th, 2023. The simulation, using the flowmeter, took between 4 and 7 minutes, 7.6 or 4.4 liters per minute. This simulation was performed under these circumstances to evaluate the performance of the green roof systems on back-to-back storm events.

The substrate moisture contents are shown (Figure 5. 5). The Extenduct roof was at 0.2225 m3/m3, the sponge roof was at 0.1797 m3/m3, and the purple roof was at 0.1848 m^3/m^3. However, even with those high substrate moisture contents, all three green roofs system retained more than 50% of the inflow water. The runoff volume is represented by the bar chart and axis on the right side of the graph. The Extenduct Roof retained the biggest volume, 23.3 liters, followed by the Sponge Roof, with 18.8 liters of volume retention, and the Purple Roof, with 17.24 liters. The runoff coefficients were 0.24 for the Extenduct Roof, 0.38 Sponge Roof, and 0.43 Purple Roof.

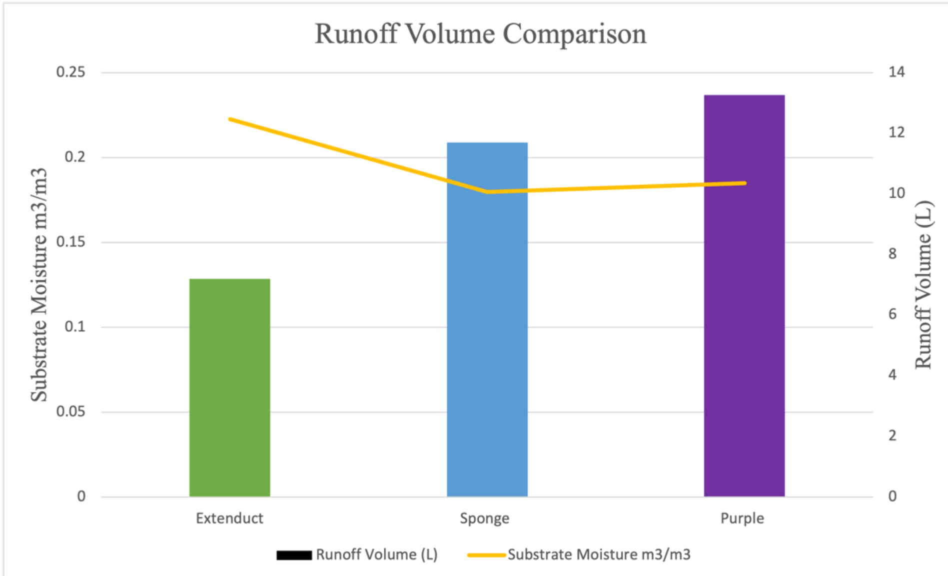

Figure 5. 5- Runoff Volume Comparison and Substrate Moisture Content between Extenduct Roof, Sponge Roof, and Purple Roof on April 7, 2023, for the WQVC simulation.

The Water Quality Capture Volume simulation behavior of each green roof system are represented (Figure 5. 6, Figure 5. 7, Figure 5. 8). The Water Input (L/min) is shown on the right axis, with the bar chart, which represents the amount of inflow water per minute in each green roof system. The line chart represents the Flow Rate (L/min), which is the volume of runoff water per second.

The Extenduct Roof behavior during the simulation had a runoff delay of 4 minutes, the highest runoff delay for this simulated event, and a discharge time of 47 minutes (Figure 5. 6). Sponge Roof (Figure 5. 7) had a runoff delay of 2 minutes and a discharge time of 55 minutes. And Purple Roof (Figure 5. 8) with a runoff delay of 3 minutes and a discharge time of 51 minutes.

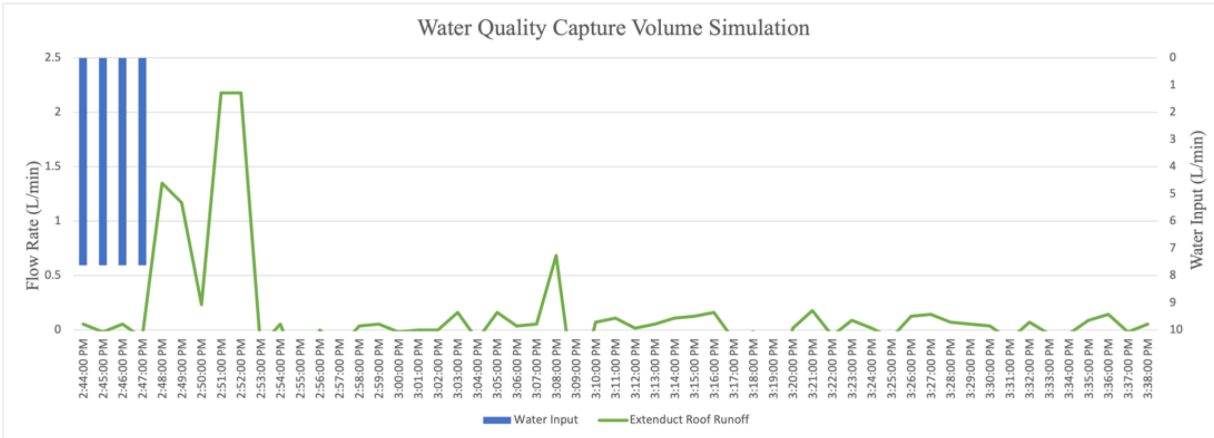

Figure 5. 6- Water Quality Capture Volume simulation event on the Extenduct Roof on April 7, 2023, for the WQVC simulation.

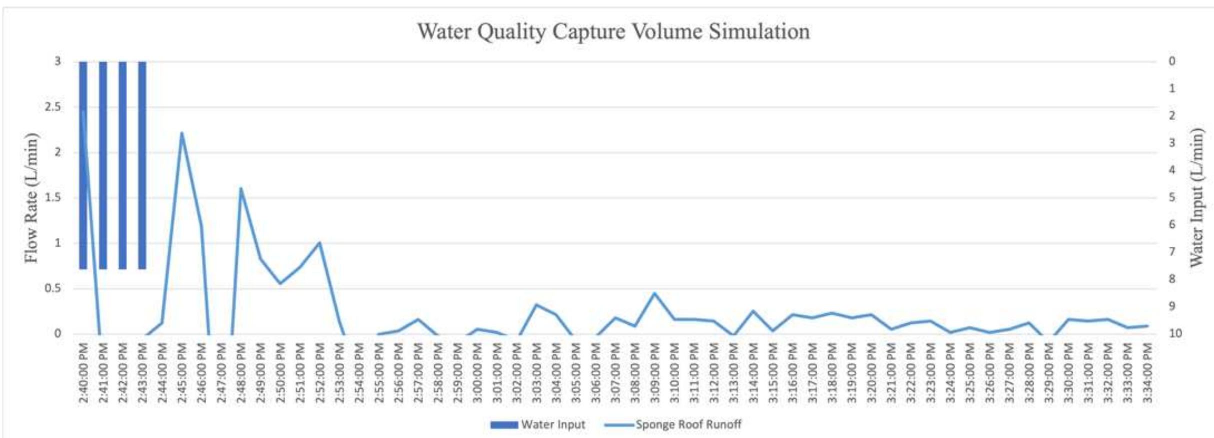

Figure 5. 7- Water Quality Capture Volume simulation event on the Sponge Roof on April 7, 2023, for the WQVC simulation.

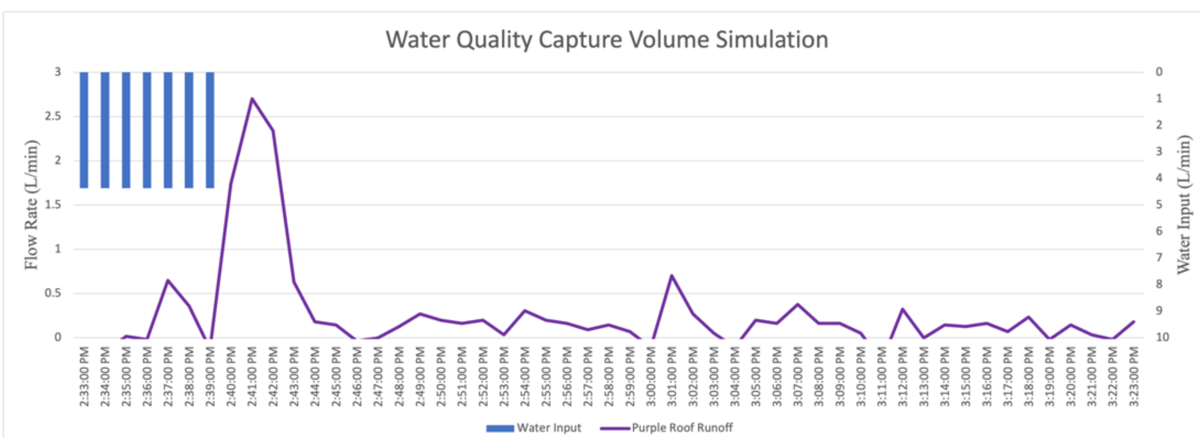

Figure 5. 8- Water Quality Capture Volume simulation event on the Purple Roof on April 7, 2023, for the WQVC simulation.

On April 22nd, 2023, there was a 2 mm rain event. The runoff volume and substrate moisture content of each green roof system is presented (Figure 5. 9). All the green roofs with high substrate moisture content, Extenduct Roof with 0.1899 m3/m3, Sponge Roof with 0.1528 m3/m3, and Purple Roof with 0.179 m3/m3, as represented by the line chart axis on the left side of the graph. The runoff volume is represented by the bar chart, which is the axis on the right side of the graph. For this event, the Extenduct Roof, Sponge Roof, and Purple Roof had no runoff volumes, 0 liters, or 100% of volume retention. Runoff only occurs from the Control Roof, with 4.3 liters.

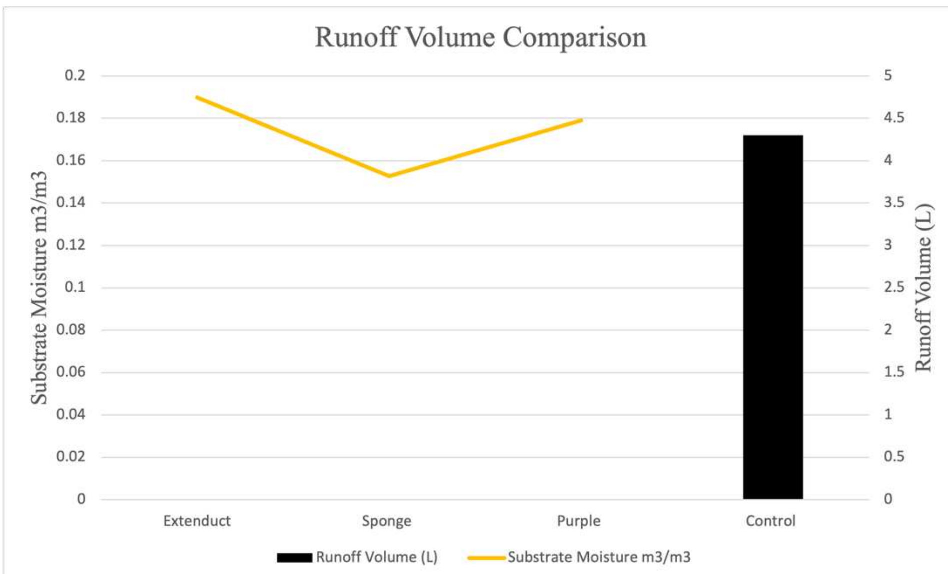

Figure 5. 9- Runoff Volume Comparison, substrate moisture content versus runoff volume, between Extenduct Roof, Sponge Roof, Purple Roof, and Control Roof

After the rain event on April 22nd, an 8 mm rain event happened on the 25th, extending its duration until the next morning, April 26th. The runoff volume and substrate moisture content of each green roof system are presented (Figure 5. 10). All the green roofs had high substrate moisture content, due to the previous rain event. The Extenduct Roof had 0.1899 m^3/m^3, Sponge Roof had 0.1521 m^3/m^3, and Purple Roof had 0.1768 m^3/m^3, as represented by the line chart, with axis on the left side of the graph.

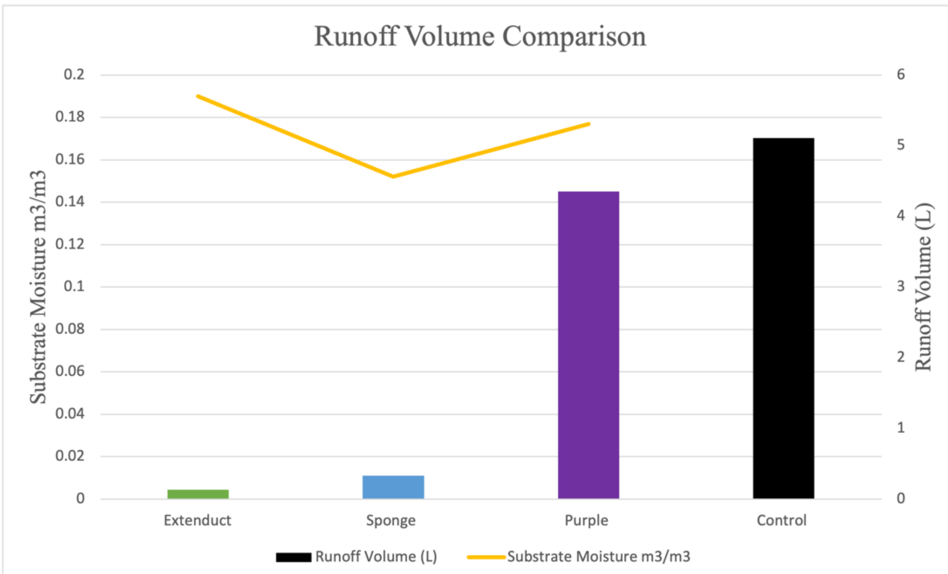

Figure 5. 10- Runoff Volume Comparison, substrate moisture content versus runoff volume, between Extenduct Roof, Sponge Roof, Purple Roof, and Control Roof

The runoff volume is represented by the bar chart, axis on the right side of the graph (Figure 5. 10). The Extenduct Roof had the greatest volume retention, 4.98 liters, followed by the Sponge Roof, with 4.78 liters, and the Purple Roof, with 0.76 liters, compared to 5.11 liters from the Control Roof. The runoff coefficients were 0.01 for the Extenduct Roof, 0.02 for the Sponge Roof, 0.27 for the Purple Roof, and 0.32 for the Control Roof.

The 8mm rain event behavior of each green roof system and the control roof are represented (Figure 5. 11, Figure 5. 12, Figure 5. 13, Figure 5. 14). The precipitation (mm) is shown on the right axis, with the bar chart, which represents the amount of rainwater. The line chart represents the Flow Rate (L/min), which is the volume of runoff water per minute.

The Control Roof starts its runoff at 2:10 pm on April 25^{th}, at the same time as the rain, with a steady outflow until the rain intensity increases, stopping at 10:04 am on April 26^{th} (Figure 5. 11). The Extenduct Roof has its runoff starting just on the next day, April $26^{th,}$ at 11:45 am; delay of 19 hours and 35 minutes, taking 42 minutes to stop the runoff (Figure 5. 12). While the Sponge Roof had a runoff delay of 18 hours and 44 minutes, taking 1 hour and 34 minutes to stop the runoff (Figure 5. 13). Purple Roof had a runoff delay of 1 hour and 42 minutes, with its runoff lasting 4 hours and 17 minutes (Figure 5. 14).

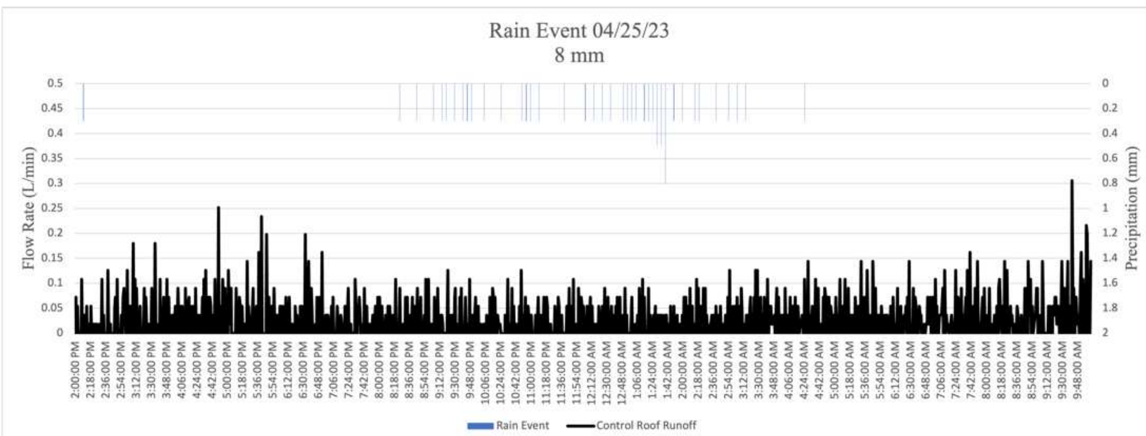

Figure 5. 11- 8mm rainfall event on the Control Roof on April 25^{th}, 2023.

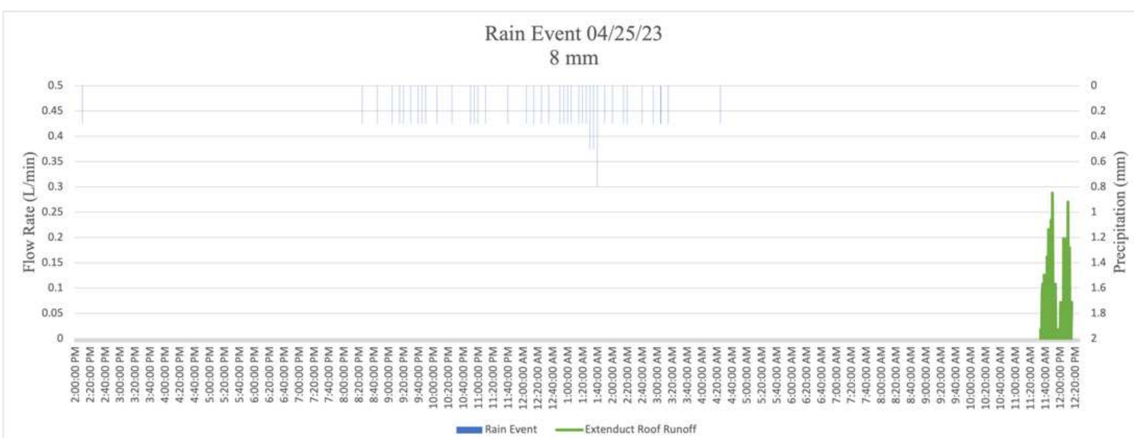

Figure 5. 12- 8mm rainfall event on the Extenduct Roof on April 25^{th}, 2023.

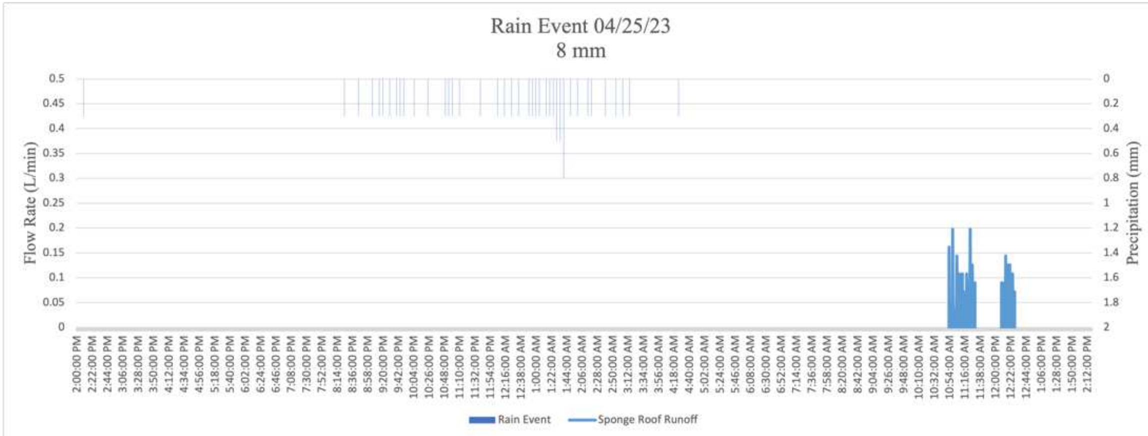

Figure 5. 13- 8mm rainfall event on the Sponge Roof on April 25th, 2023.

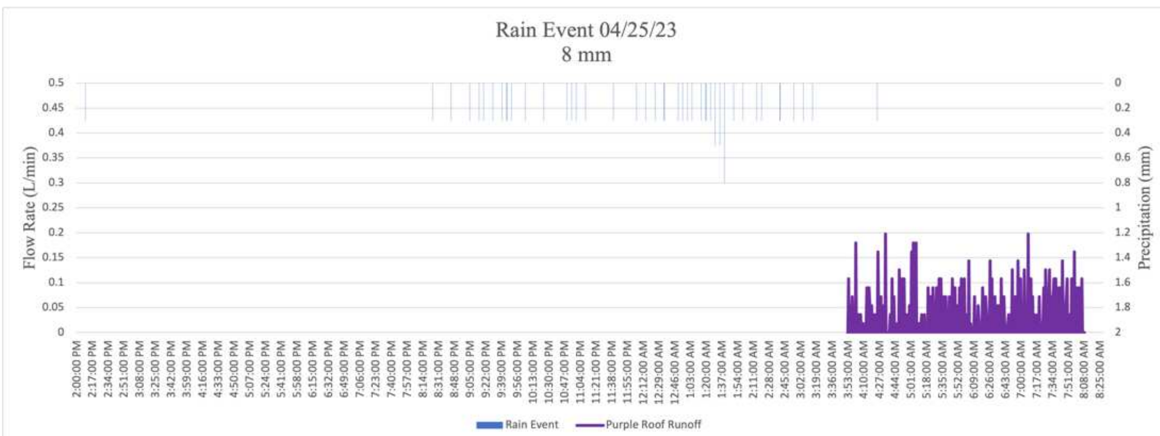

Figure 5. 14- 8mm rainfall event on the Purple Roof on April 25th, 2023.

From May 9th to May 15th, 2023, it was registered in Fort Collins a rainfall event of 75 mm in total. The runoff volume and substrate moisture content of each green roof system are presented (Figure 5. 15. All the green roofs had high substrate moisture content, the Extenduct Roof with 0.1455 m^3/m^3, the Sponge Roof with 0.1209 m^3/m^3, and the Purple Roof with 0.1426 m^3/m^3, as represented by the line chart, axis on the left side of the graph.

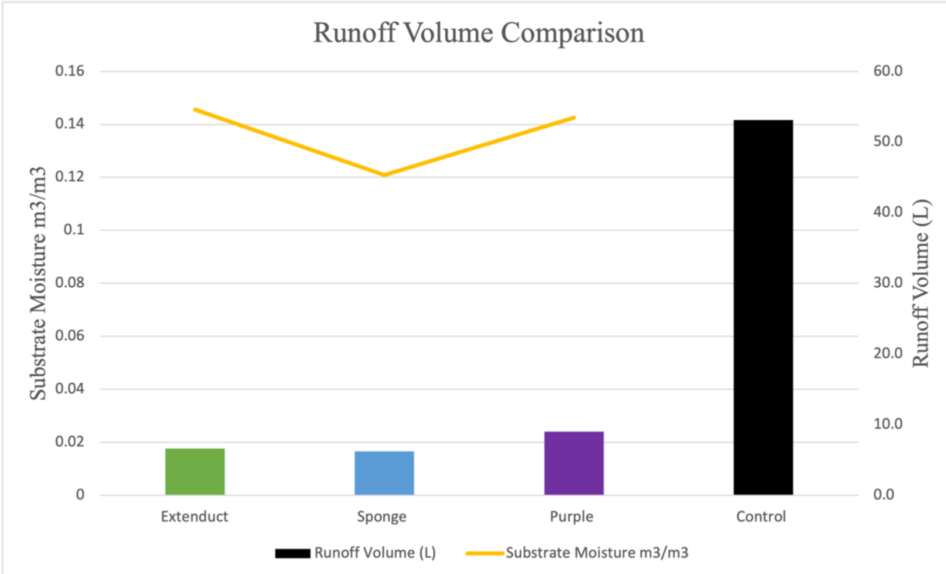

Figure 5. 15- Runoff Volume Comparison, substrate moisture content versus runoff volume, between the Extenduct Roof, Sponge Roof, Purple Roof, and Control Roof

The runoff volume is represented by the bar chart, axis on the right side of the graph (Figure 5. 15). The Extenduct Roof had a volume retention of 46.5 liters, the Sponge Roof had 46.9 liters, and the Purple Roof, 44.1 liters, compared to 53.1 liters outflowed from Control Roof. The runoff coefficients were 0.04 for the Extenduct Roof and the Sponge Roof, 0.06 for the Purple Roof, and 0.35 for the Control Roof.

The 75 mm rain event behavior of each green roof system and the Control Roof are represented (Figure 5. 16, Figure 5. 17, Figure 5. 18, Figure 5. 19). The precipitation (mm) is shown on the right axis, with the bar chart, which represents the amount of rainwater. The line chart represents the Flow Rate (L/min), which is the volume of runoff water per minute.

The Control Roof starts its runoff at 12:13 pm on May 11th, stopping at 9:16 am on May 15th (Figure 5. 16). The Extenduct Roof has its runoff starting on May 11th at 8:52 pm; delay of 8 hours and 39 minutes, stopping at 8:18 am on May 15th (Figure 5. 17). The Sponge Roof has its runoff starting on May 11th at 10:00 pm; delay of 9 hours and 47 minutes, stopping at 8:22 am on May 15th (Figure 5. 18). The Purple Roof has its runoff starting on May 11th at 11:56 am; delay of 2 hours and 40 minutes, stopping at 7:57 am on May 15th (Figure 5. 19).

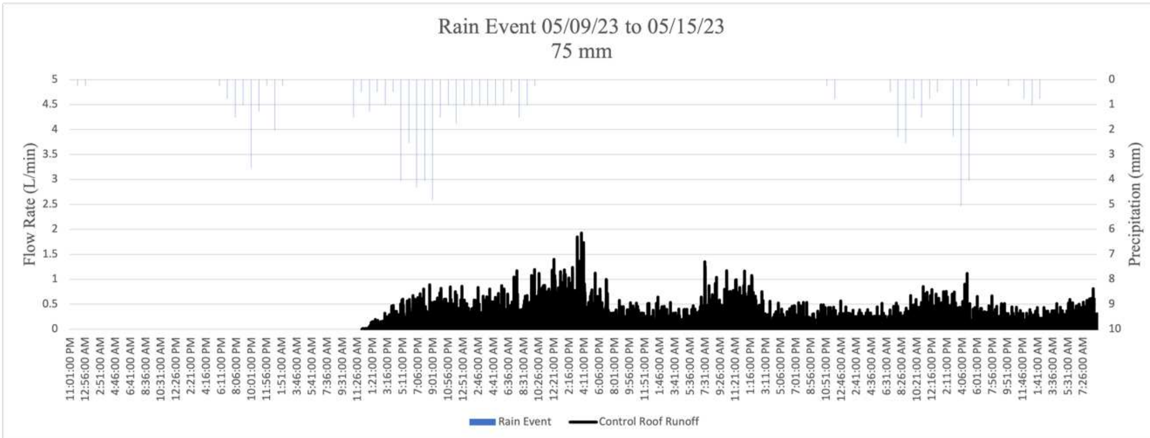

Figure 5. 16- 75 mm rainfall event on the Control Roof from May 09th to May 15th, 2023.

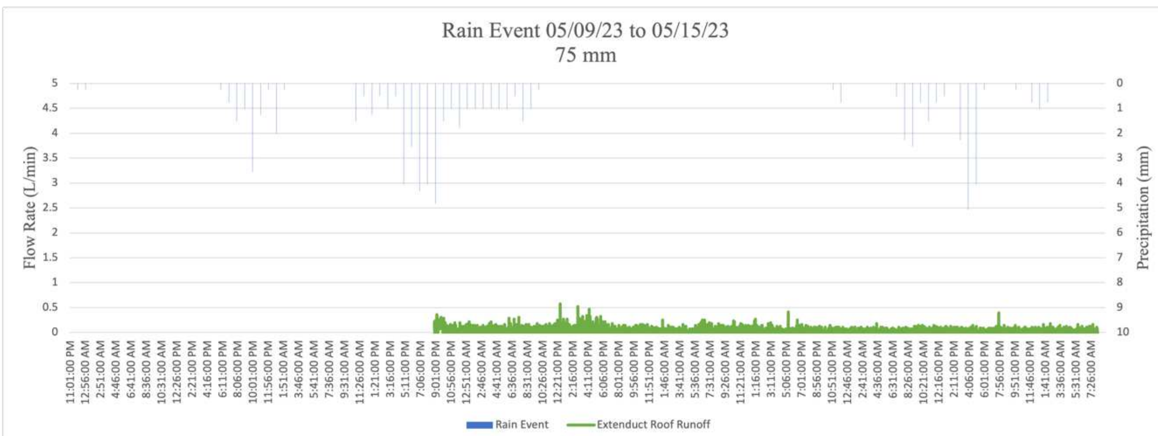

Figure 5. 17- 75 mm rainfall event on the Extenduct Roof from May 09th to May 15th, 2023.

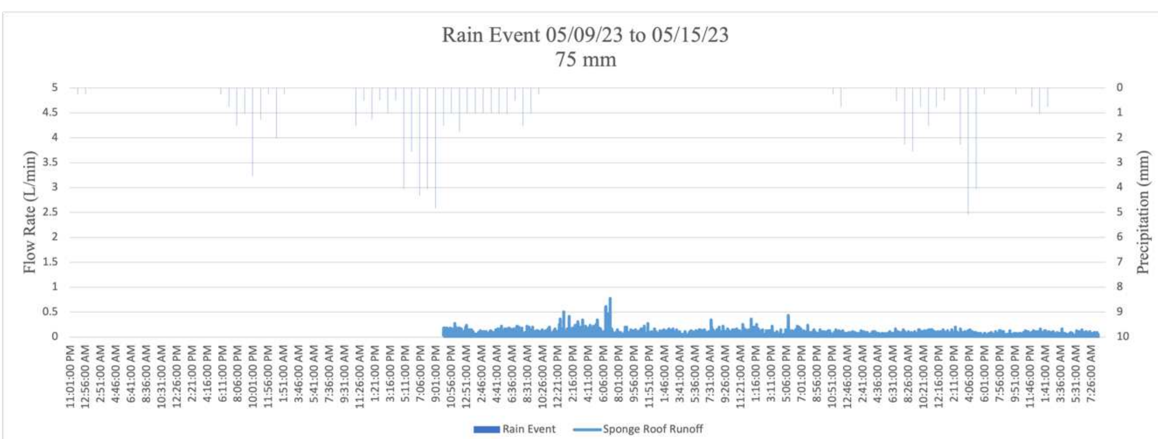

Figure 5. 18- 75 mm rainfall event on the Sponge Roof from May 09th to May 15th, 2023.

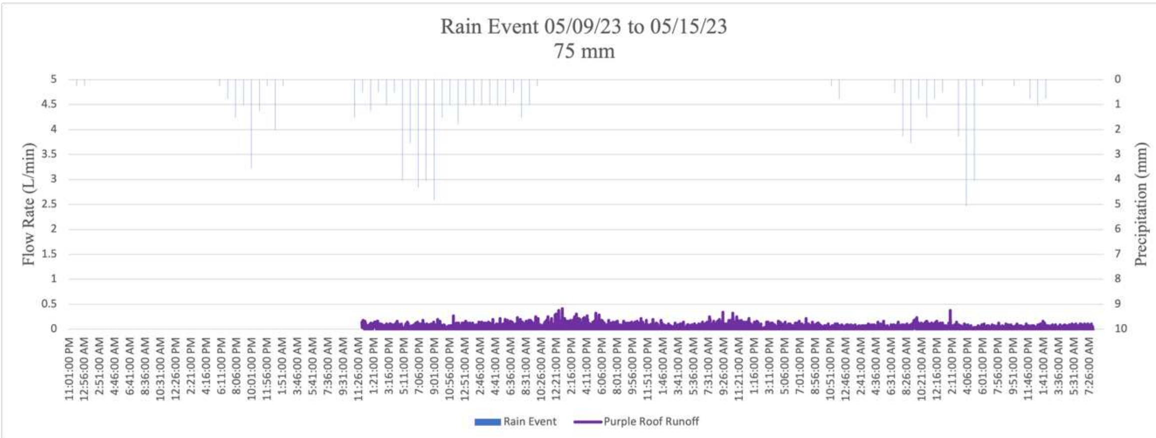

Figure 5. 19- 75 mm rainfall event on the Purple Roof from May 09th to May 15th, 2023.

On May 16th, 2023, a rainfall event of 2 mm was registered in Fort Collins. The runoff volume and substrate moisture content of each green roof system are presented (Figure 5. 20. All three green roofs had high substrate moisture content, the Extenduct Roof with 0.2109 m^3/m^3, the Sponge Roof with 0.1761 m^3/m^3, and the Purple Roof with 0.1681 m^3/m^3, as represented by the line chart, with the axis on the left side of the graph.

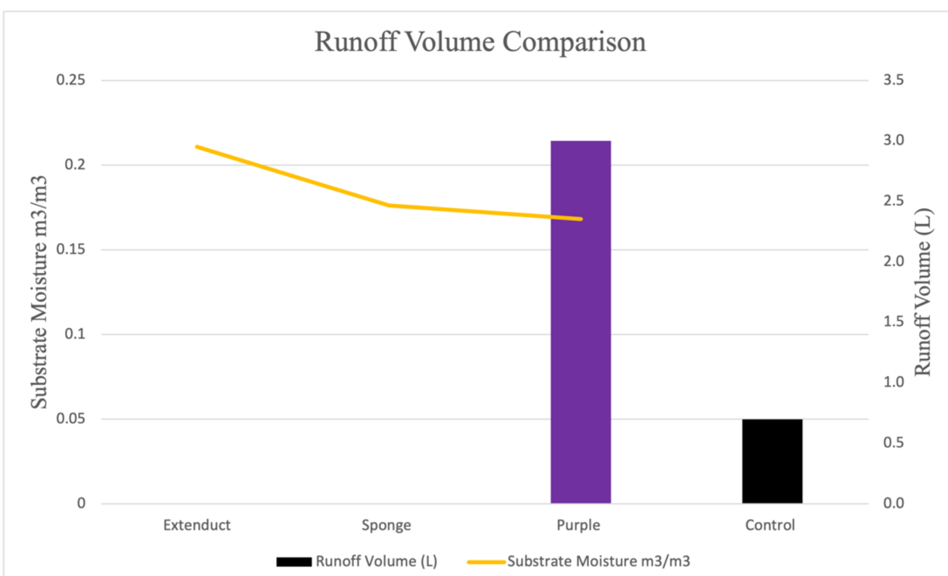

Figure 5. 20- Runoff Volume Comparison, substrate moisture content versus runoff volume, between Extenduct Roof, Sponge Roof, Purple Roof, and Control Roof

The runoff volume is represented by the bar chart, axis on the right side of the graph (Figure 5. 20). For this event, Extenduct Roof and Sponge Roof had no runoff volumes, 0 liters, or 100% of volume retention. Runoff only occurs from the Control Roof, with 0.7 liters, and from the Purple Roof, with 3 liters.

The 2 mm rain event behavior of the Control Roof and the Purple Roof system are represented (Figure 5. 21 and Figure 5. 22). The precipitation (mm) is shown on the right axis, with the bar chart, which represents the amount of rainwater. The line chart represents the flow rate (L/min), which is the volume of runoff water per minute.

The Control Roof starts its runoff at 6:10 am on May 16th, stopping at 6:21 am on the same day (Figure 5. 21). The Purple Roof has its runoff starting on May 18th at 11:59 pm, stopping at 7:32 am on May 19th (Figure 5. 22). The runoff coefficients were 0.75 for the Purple Roof and 0.18 for the Control Roof, taking into consideration the rain event of only 2mm.

Analyzing the Purple Roof runoff behavior, it is assumed that its runoff occurred because of the saturation of its water retention layer and weather conditions. With the initial high substrate moisture content and an increase in ambient air temperature, the Purple Roof did yield runoff. Because its layers were saturated from previous rain events, as it has a water retention layer with a higher water holding capacity, it generated an outflow of the system due to gravity and additional rainwater from a previous precipitation event.

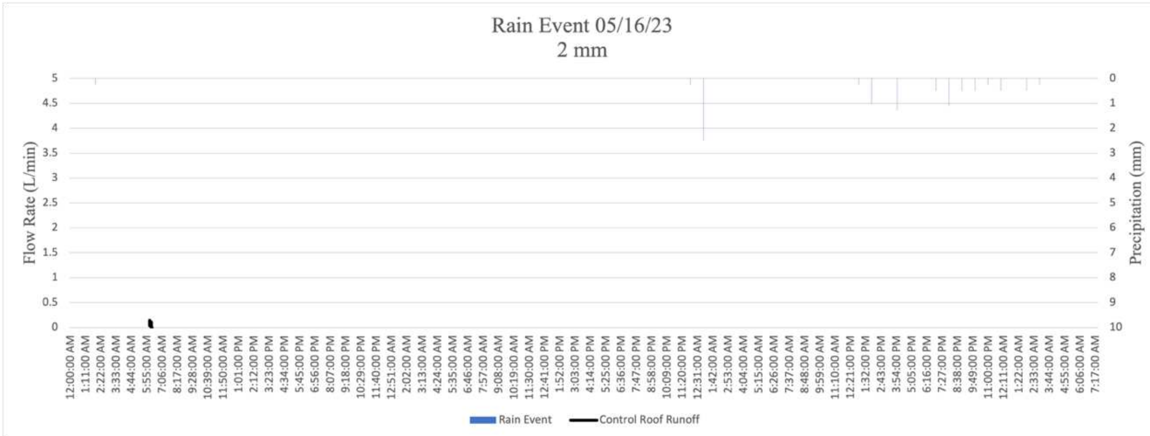

Figure 5. 21- 2 mm rainfall event on the Control Roof on May 16th, 2023.

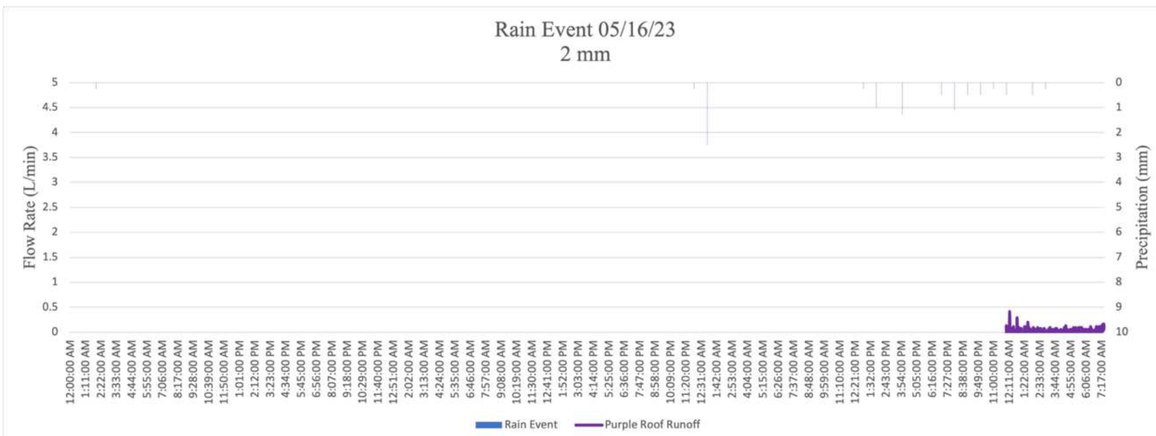

Figure 5. 22- 2 mm rainfall event on the Purple Roof on May 16th, 2023.

As previously mentioned in Section 3.3.2, when the substrate moisture content is between field capacity and saturation, some water continues to advance the wetting front, and some moves through the substrate to the drainage layer, pull by gravity. The hydrological hypothesis is that on a green roof if the substrate moisture is below field capacity and the rain event is not intense, there is a chance of no runoff from a green roof system. However, after field capacity is reached, the runoff will probably happen. When runoff occurs from mild rain events of long duration, it indicates that the substrate has achieved a saturated point.

For a more contextual and graphical view and comparison, Figure 5. 23 and Figure 5. 24 show the behavior of each green roof, Extenduct Roof, Sponge Roof, and Purple Roof, during all the precipitation events, natural or simulated, converted to mm. The solid bars represent the runoff volume in liters (Figure 5. 24), and the bars with vertical stripes (Figure 5. 23), indicate the volume retention of each green roof for the respective precipitation event. The symbols represent the substrate moisture content of each green roof. The green circle represents the substrate moisture content (m^3/m^3) for the Extenduct Roof, the purple triangle, the substrate moisture content (m^3/m^3) of the Purple Roof, and the blue square, the substrate moisture content (m^3/m^3) of the Sponge Roof.

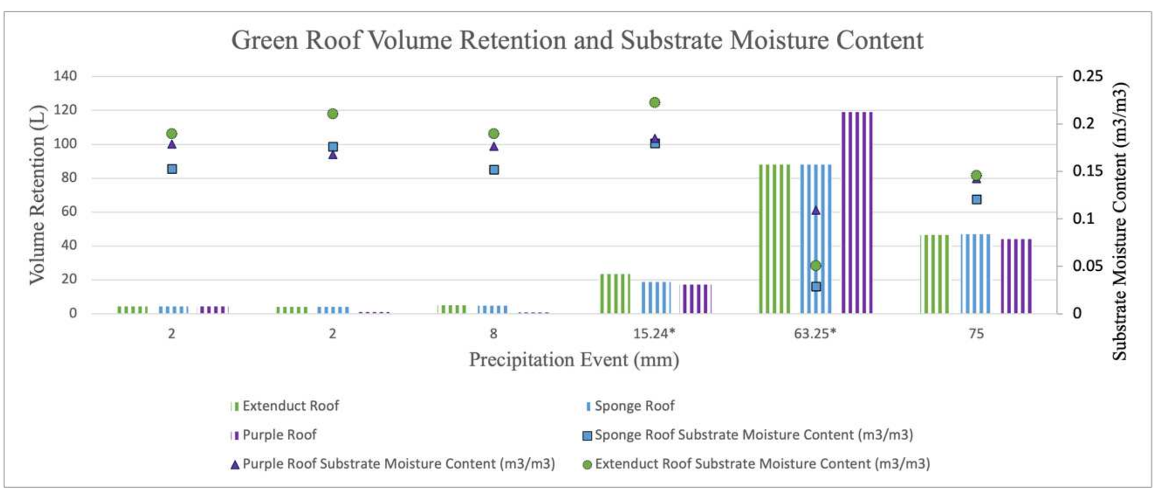

*Figure 5. 23 – Green Roof Volume Retention and Substrate Moisture Content for Extenduct Roof, Sponge Roof, and Purple Roof. * Represents the simulation events where it was used a known volume of precipitation to calculate volume retention. The other events used control roof as a baseline for water retention volumes.*

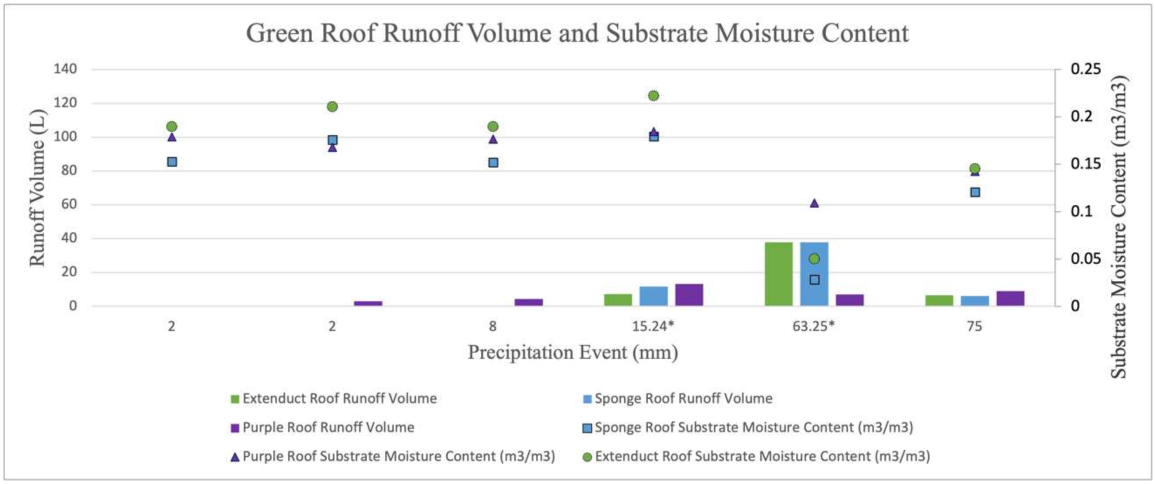

*Figure 5. 24 - Green Roof Runoff Volume and Substrate Moisture Content for Extenduct Roof, Sponge Roof, and Purple Roof. * Represents the simulation events where it was used a known volume of precipitation to calculate runoff volume. The other events used control roof as a baseline for water runoff volume.*

Another way to evaluate the green roofs' substrate moisture content and the runoff coefficient, the runoff volume per total rain volume, is represented by Figure 5. 25. The line chart represents the Runoff Coefficient and by the symbols, the substrate moisture content of each green roof. Where it is possible to see that Purple Roof with substrate moisture content above 0.15 m^3/m^3 has a high runoff coefficient. Indicating that it will retain bigger volumes of water when the substrate moisture is below 0.15 m^3/m^3. Extenduct Roof and Sponge had a similar pattern of runoff coefficient, indicating that water volume retention is more related to the size of the precipitation event than the previous substrate moisture content.

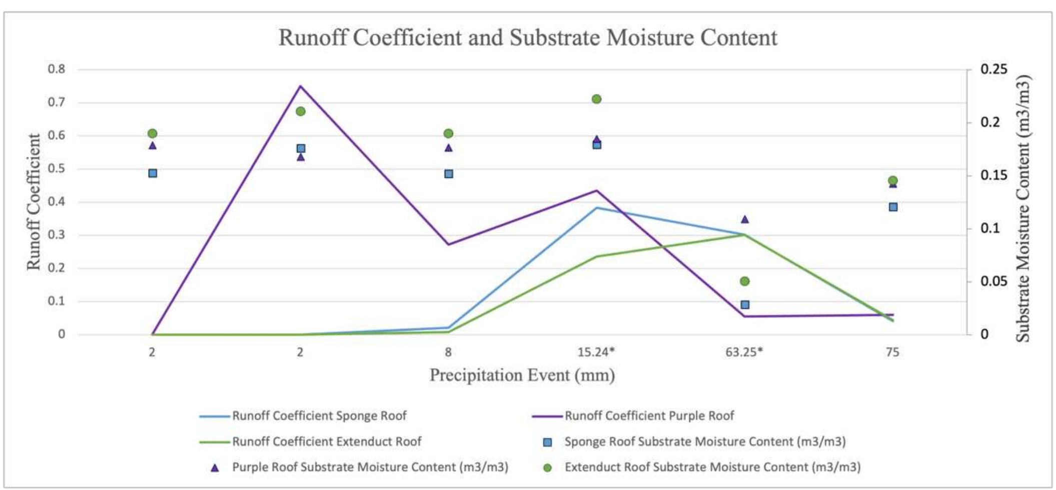

*Figure 5. 25 - Runoff Coefficient and Substrate Moisture Content for Extenduct Roof, Sponge Roof, and Purple Roof. * Represents the simulation events where it was used a known volume of precipitation to calculate runoff volume. The other events used control roof as a baseline for water runoff volume.*

5.1.2 Substrate Moisture Retention and Components for Better Water Capture

To draw a relation between substrate moisture content and water capture in a green roof, some aspects were considered. As the substrate and vegetation were the same across all three green roof systems, the water retention layers were the main factors to be evaluated to see how they could influence each green roof in terms of water-holding capacity.

The hydrological hypothesis for a green roof behavior is that the rainwater will be retained inside the system after a low volume, short duration rainfall event. If the substrate has a substrate moisture content below field capacity, barely any runoff will occur. The vegetation will absorb a portion of the water in the system, and evapotranspiration will happen. Evapotranspiration rates are dependant on weather conditions. However, if the rainfall event is over a long duration, the substrate will be close to its field capacity, generating a more considerable runoff, drained by gravity (Bengtsson, 2005).

The substrate moisture content (m^3/m^3) is represented by the line chart on the left axis and the precipitation (mm) from natural and simulated rain events by bar chart on the right axis on all three green roof systems (Figure 5. 26). The Extenduct Roof is represented in green, the Sponge Roof in blue, and the Purple Roof, in purple. The first six months of data, June to December 2022, shows that the Extenduct Roof and Sponge Roof had a greater variation in substrate moisture content immediately after water input than the Purple Roof. However, during the winter and spring seasons, it is possible to see all three green roof systems in a more consistent and aligned pattern. Even with the Extenduct Roof and Sponge Roof varying more than the Purple Roof, they had a smaller amplitude and variation.

When the standard variation between the Sponge Roof and the Purple Roof substrate moisture was used to compare their variation in amplitude, it was shown that during the months of July and October, it had the biggest values, around 0.04. During the other months, the Purple Roof had a greater substrate moisture content than the Sponge Roof, supporting the idea that the honeycomb system would provide more moisture to the system.

Bengtsson et al. (2005) explain that the substrate often dries out in the summer between storms. In a few days, the substrate can dry out to near wilting point conditions. Figure 5. 26 We see this trend when the substrate had almost 0.3 (m^3/m^3) moisture content after a rainfall event in August 2022, and one week later it was near 0.15 (m^3/m^3) (Figure 5. 26). However, we can still see this happening in December 2022, during winter. Therefore, after an intense rainfall simulation, this significant dry-down in December 2022 can be associated with the low relative humidity (as low as 28% on 12/16/2022) and low temperatures (-22˚C on 12/22/2022).

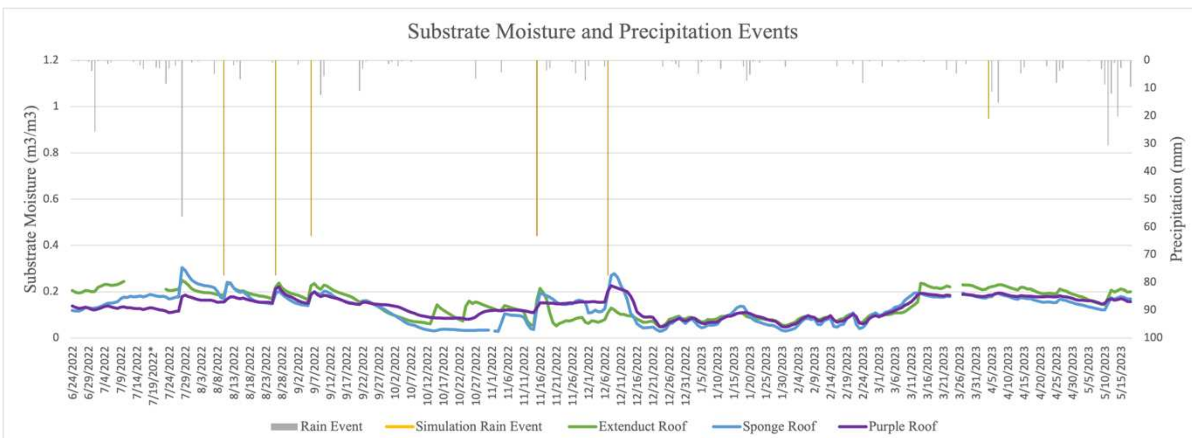

Figure 5. 26- Extenduct Roof, Sponge Roof, and Purple Roof substrate moisture content (m3/m3) and precipitation events between June 2022 and May 2023.

During the winter, from January 2023 to February 2023, the lower temperatures resulted in decreased substrate moisture (Figure 5. 26). But when the temperatures increased in March 2023, the substrate moisture content in all three green roofs also increased. This can be related to the phenomenon of defrosting directly affecting the water availability in the substrate.

5.2 Plant health

To analyze plant health and survivability in all three green roof systems, Extenduct Roof, Sponge Roof, and Purple Roof, for this study, it was selected the criteria of visual health, vegetation colors and growth, and moisture content of the substrate.

The vegetation was placed on the three green roofs in May 2022. For their establishment, overhead sprinklers were used from June to July 2022. In total, the green roof systems were irrigated 15 times. Five of those times were for irrigation audits. The average temperature for this period was 23˚C, and the air's relative humidity was 48%.

When irrigation started in June 2022, the average substrate moisture content was 0.20 (m^3/m^3) for the Extenduct Roof, 0.05 (m^3/m^3) for the Sponge Roof, and 0.06 (m^3/m^3) for the Purple Roof. In July 2022, when irrigation was stopped because of rainfall events and simulation events were initiated, the moisture content of the green roofs' substrate was 0.21 (m^3/m^3) for the Extenduct Roof, 0.18 (m^3/m^3) for the Sponge Roof, and 0.12 (m^3/m^3) for the Purple Roof (Figure 5. 27).

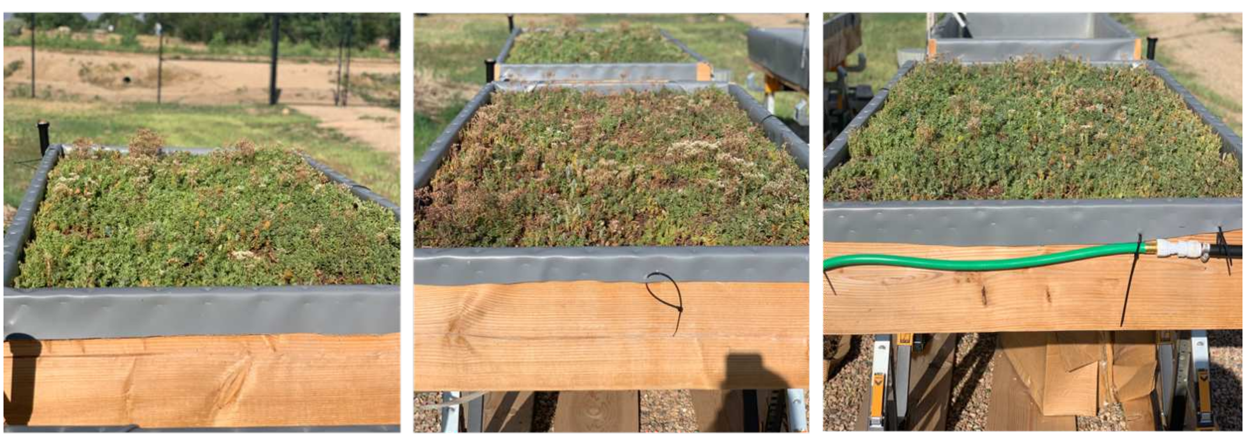

Figure 5. 27 – Vegetation established in July 2022. Extenduct roof, sponge roof, and purple roof, from left to right.

In October 2022, the substrate moisture content of all three green roofs was low again, 0.10 (m^3/m^3) for the Extenduct Roof, 0.03 (m^3/m^3) for the Sponge Roof, and 0.08 (m^3/m^3) for the Purple Roof. In October, two irrigations were conducted, 20 liters of water in each green roof, this time without the overhead sprinklers. Instead, we used a flowmeter connected to a garden hose. Besides the very low substrate moisture content, an average of 0.14 (m^3/m^3) for the Extenduct Roof, 0.04 (m^3/m^3) for the Sponge Roof, and 0.08 (m^3/m^3) for the Purple Roof, the vegetation had a very healthy appearance (Figure 5. 28). After those two days of irrigation, the rain and snow restarted.

Figure 5. 28- Vegetation in October 2022. Extenduct roof, sponge roof, and purple roof, from left to right.

The vegetation did not receive any extra maintenance besides some weed removal and irrigation, surviving during the driest (average of 25 % relative humidity in April 2023) and wettest (average of 93% relative humidity in September 2022 and January 2023) periods with the lowest (day average of -22 ˚C in December 2022) and highest (day average of 28˚C in July 2023) temperatures. No addition of nutrients was required. After an entire year, the vegetation remained viable (Figure 5. 29). Some portions of the vegetation will need to be replanted, as all green roofs require maintenance. Coming out of dormancy the plants vary by treatment (Table 5 1). Variation occurred due to sedum's species during overwintering.

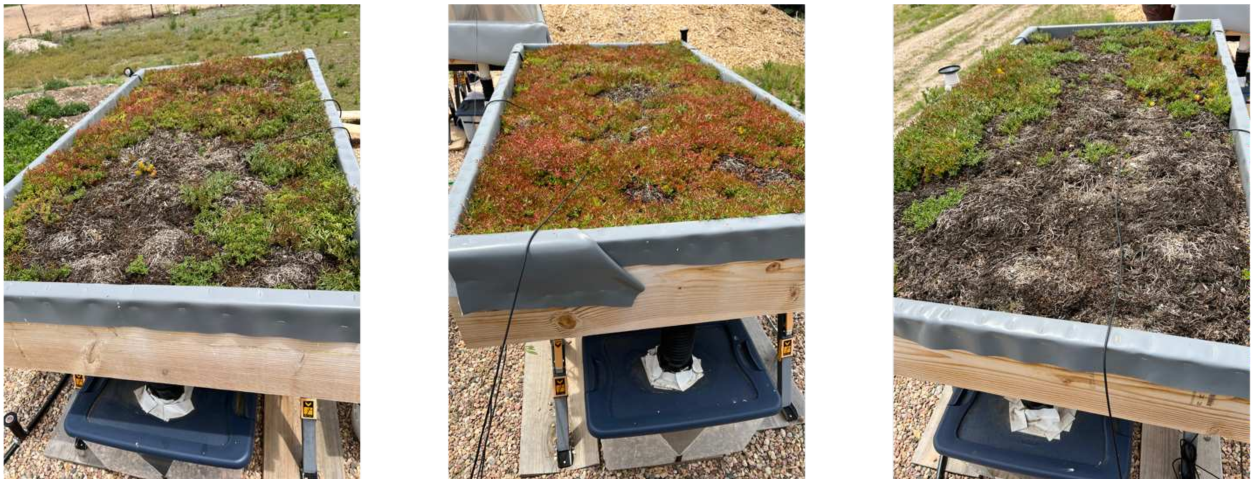

Figure 5. 29- Vegetation in May 2023. Extenduct Roof, Sponge Roof, and Purple Roof, from left to right.

Table 5 1- Ex-Post Facto Analysis of plant cover over time. D represents dormancy.

Dates	Extenduct Roof Percentage Cover	Sponge Roof Percentage Cover	Purple Roof Percentage Cover	Average Percentage Cover
May 2022	100 %	100 %	100 %	100 %
June 2022	100 %	100 %	100 %	100 %
July 2022	100 %	100 %	100 %	100 %
August 2022	100 %	100 %	100 %	100 %
September 2022	100 %	100 %	100 %	100 %
October 2022	100 %	100 %	100 %	100 %
November 2022	100 %	100 %	100 %	100 %
December 2022	100 %	100 %	100 %	100 %
January 2023	D	D	D	D
February 2023	D	D	D	D
March 2023	D	D	D	D
April 2023	15%	33%	2%	16.67%
May 2023	45%	85%	33%	54.33%

6. Conclusion

The analysis of each green roof system compared to a Control Roof in different rain events, simulated or natural, shows that substrate moisture content and specific components, such as water detention layers, had the most influence on the stormwater capture results.

Extenduct Roof and Sponge Roof had the same behavior when we analyze the runoff coefficient and volume retention for all the precipitation events. Where with high or low substrate moisture content the volume retention between them is almost the same. Purple Roof, on the other hand, had runoff coefficients higher than 0.2 when there was a high substrate moisture content, more than 0.15 m^3/m^3; and runoff coefficient of less than 0.1 when its substrate moisture content was less than 0.15 m^3/m^3. Represent in this way a strong correlation between substrate moisture content and volume retention for Purple Roof.

Natural rain events that happened in April show that the Extenduct Roof and Sponge Roof, besides their less complex design, worked better to capture small rain events in back-to-back scenarios. On the other hand, the Purple Roof, with blue-green roof components, had a reduced storage capacity in its retention and detention layer, leading to a small retention capacity on a small rain event but a significant runoff delay. A larger and long-duration rain event, such as the one in May 2023, shows all three green roofs having tremendous volume retention capacity when compared to a conventional roof.

The WQCV simulation resulted in the Extenduct Roof capturing the largest volume of water, more than the Sponge Roof and Purple Roof. As the Extenduct Roof has a less complex water capture layer, its dry down occurs faster than the other green roof systems. Considering their substrate moisture content, it is assumed that the Sponge Roof and the Purple Roof had their water detention and retention layers near the saturation point, generating a larger runoff.

The 50-year rainfall simulation represents an interesting scenario, different from the other analysis. For this event, the substrate moisture content was lower, more ideal for water detention and retention. With this more favorable situation, the Purple Roof had an outstanding performance in comparison with the Extenduct Roof and the Sponge Roof.

With these results, it is plausible to assume that the Purple Roof, with its water capture components combined with a low substrate moisture content, will perform better than the Extenduct Roof and Sponge Roof systems in bigger rain events that might lead to flooding and urban drainage concerns in cities. Conversely, less intense and more frequent rainfall events point to the Extenduct Roof and the Sponge Roof as more favorable systems when substrate moisture is above 0.15 m^3/m^3. Its capacity to detain water and not retain it makes its volume capture more considerable for this configuration of a rain event.

Besides the different water retention components in the green roof systems, they presented a similar behavior related to substrate moisture content before and after rain events, natural or simulated. However, the Purple Roof was the one with less amplitude variation when compared to the Extenduct Roof and Sponge Roof systems. This could be influenced by its honeycomb system, supplying water to the substrate gradually.

All three green roof systems' vegetation were acceptable aesthetically and had adequate plant health in all seasons. With plant health increasing over time in the spring. Irrigation demand was low, just enough for plant establishment.

References

Andenæs, E., Kvande, T., Muthanna, T. M., & Lohne, J. (2018). Performance of Blue-Green Roofs in Cold Climates: A Scoping Review. Buildings, 8(4), 55. https://doi.org/10.3390/buildings8040055

ASTM. (2020). ASTM E2777-20 Standard Guide for Vegetative (Green) Roof Systems. https://www.astm.org/. Retrieved March 29, 2023, from https://www.astm.org/e2777-20.html

Bengtsson, L., Grahn, L., & Olsson, J. (2005). Hydrological function of a thin extensive green roof in southern Sweden. Hydrology Research, 36(3), 259–268. https://doi.org/10.2166/nh.2005.0019

Bilskie, J. (2001). Soil water status: content and potential. Campbell Scientific, Inc. Retrieved January 13, 2023, from http://s.campbellsci.com/documents/cn/technical-papers/soilh20c.pdf

Blount, K., Abdi, R., Panos, C. L., Ajami, N. K., & Hogue, T. S. (2021). Building to conserve: Quantifying the outdoor water savings of residential redevelopment in Denver, Colorado. Landscape and Urban Planning, 214, 104178. https://doi.org/10.1016/j.landurbplan.2021.104178

Bonham, C. D. (2013). Measurements for terrestrial vegetation. John Wiley & Sons.

Busker, T., De Moel, H., Haer, T., Schmeits, M., Van Den Hurk, B. J. J. M., Myers, K., Cirkel, D. G., & Aerts, J. C. J. H. (2022). Blue-green roofs with forecast-based operation to reduce the impact of weather extremes. Journal of Environmental Management, 301, 113750. https://doi.org/10.1016/j.jenvman.2021.113750

Caldwell, M. M., Dawson, T. E., & Richards, J. (1998). Hydraulic lift: consequences of water efflux from the roots of plants. Oecologia, 113(2), 151–161. https://doi.org/10.1007/s004420050363

Cascone, S. (2019). Green Roof Design: State of the Art on Technology and Materials. Sustainability, 11(11), 3020. https://doi.org/10.3390/su11113020

Cassel, D. K., & Nielsen, D. S. (1986). Field Capacity and Available Water Capacity. In Soil Science Society of America book series (pp. 901–926). https://doi.org/10.2136/sssabookser5.1.2ed.c36

Cardno, T. E. C. (2012). Green roof performance study. Seattle Public Utilities, Seattle, WA.

City and County of Denver, Flood Information. (2021[a]). https://www.denvergov.org/Government/Agencies-Departments-Offices/Department-of-Transportation-and-Infrastructure/Programs-Services/Flood-Information. Accessed on 11/28/2021.

City and County of Denver, Rules and Regulations Governing Green Building Requirements (2021[b]). Department Of Community Planning and Development and Office Of Climate Action, Sustainability, and Resiliency Rules Governing Green Building Requirements. https://www.denvergov.org/files/assets/public/community-planning-and-development/documents/ds/gbo/gbo_rules_regs.pdf

City of Philadelphia (2023), Green Roof Tax Credit - Services. (2023). https://www.phila.gov/services/payments-assistance-taxes/taxes/tax-credits/business-tax-credits/green-roof-tax-credit/

Cobos, D. R., & Chambers, C. (2010). Calibrating ECH2O soil moisture sensors. Application note, 1-5.

Connelly, M., & Liu, K. (2005). Green roof research in British Columbia: An overview. In Proc. of 3rd North American Green Roof Conference: Greening rooftops for sustainable communities, Washington, DC (pp. 4-6).

CWCB (2023). Colorado Water Conservation Board. Department of Natural Resources. Hazards | DNR CWCB. https://cwcb.colorado.gov/focus-areas/hazards

CWCB (2019). Colorado Water Conservation Board. Department of Natural Resources. Colorado's Water Plan. Volume 1, Sections 4.1 and 4.2 - Statewide Results.

Dunkerley, D. (2008). Rain event properties in nature and in rainfall simulation experiments: a comparative review with recommendations for increasingly systematic study and reporting. Hydrological Processes, 22(22), 4415–4435. https://doi.org/10.1002/hyp.7045

EPA, 2022. Combined Sewer Overflows (CSOs) | US EPA. (2022, June 22). US EPA. https://www.epa.gov/npdes/combined-sewer-overflows-csos

EPA, 2023. NPDES Stormwater Program | US EPA. (2023b, February 2). US EPA. https://www.epa.gov/npdes/npdes-stormwater-program

Fioretti, R., Palla, A., Lanza, L., & Principi, P. (2010). Green roof energy and water related performance in the Mediterranean climate. Building and Environment, 45(8), 1890–1904. https://doi.org/10.1016/j.buildenv.2010.03.001

Getter, K. L., & Rowe, D. E. (2006). The Role of Extensive Green Roofs in Sustainable Development. Hortscience, 41(5), 1276–1285. https://doi.org/10.21273/hortsci.41.5.1276

GRHC, (2013). Green Roofs for Healthy Cities. "Green Roof Design and Installation - Resource Manual" 2013. https://green-roofs-bg8t.squarespace.com/greeninfrastructurestore/green-roof-design-and-installation-digital

Hoang, L., & Fenner, R. A. (2014, September). System interactions of green roofs in blue-green cities. In Proceedings of the 13th International Conference on Urban Drainage, Sarawak, Malaysia (pp. 8-12).

Isco, T. (2016). Teledyne ISCO Open Channel Flow Measurement Handbook (8th ed.). Teledyne ISCO.

Onset's HOBO and InTemp Data Loggers. 12-Bit Temperature Smart Sensor (S-TMB-M0xx) Manual. https://www.onsetcomp.com/sites/default/files/resources-documents/7105-R+S-TMB+Manual.pdf. Accessed on 01/03/2023.

Onset's HOBO and InTemp Data Loggers. Soil Moisture Smart Sensor (S-SMx-M005) Manual. https://www.onsetcomp.com/sites/default/files/resources-documents/15081-J+S-SMx+Manual.pdf. Accessed on 12/06/2022.

Luthy, R. G., Sharvelle, S., & Dillon, P. J. (2019). Urban Stormwater to Enhance Water Supply. Environmental Science & Technology, 53(10), 5534–5542. https://doi.org/10.1021/acs.est.8b05913

Manso, M. E. G., Teotónio, I., Silva, C. L. M., & Cruz, C. O. (2021). Green roof and green wall benefits and costs: A review of the quantitative evidence. Renewable & Sustainable Energy Reviews, 135, 110111. https://doi.org/10.1016/j.rser.2020.110111

McIntyre, L., & Snodgrass, E. C. (2010). The green roof manual: a professional guide to design, installation, and maintenance. Timber Press.

McIntosh, A. (2010). Green Roofs in Seattle - a survey of vegetated roofs and rooftop gardens. City of Seattle and the University of Washington Green Futures Lab. Retrieved March 23, 2023, from https://www.seattle.gov/

National Weather Service. “2020 Annual Climate Summary.” (2020). www.weather.gov/bou/2020AnnualClimateSummary. Accessed on 28/11/2021.

Niu, H., Clark, C., Connelly, M., Busiek, B., & Adriaens, P. (2010). Quantitative assessment of green roof benefits for Vancouver. In Cities Alive 8th annual green roof wall conference.

Philadelphia Water Department. (2009). GSI Performance Testing | PhillyWatersheds.org. Philly Watersheds. Retrieved January 12, 2023, from http://archive.phillywatersheds.org/what_were_doing/green_infrastructure/gsi_monitoring/performance_testing

Project Groundwork. "Enabled Impact Program. Sustainable Stormwater Projects". https://www.projectgroundwork.org/downloads/ei/eip_fact_sheet.pdf. (2013). Accessed on October 13, 2021.

“Purple-Roof’s Green Roof Construction Specifications.” Purple-Roof, www.purple-roof.com/specs#detention-layer. Accessed 2 Feb. 2022.

Rowe, D.B., and Getter, K.L (2022). “Improving stormwater retention on green roofs”. Journal for living Architecture, vol 9, number 1, pp. 20-36, 2022.

Sage, R. F. (2008). Autotrophs. In Elsevier eBooks (pp. 291–300). https://doi.org/10.1016/b978-008045405-4.00851-x

Sempergreen. How much does a green roof weigh? https://www.sempergreen.com/en/solutions/green-roofs/frequently-asked-questions-green-roof/how-much-does-a-green-roof-weigh. Accessed 30 Mar. 2023

She, N., & Pang, J. (2010). Physically Based Green Roof Model. Journal of Hydrologic Engineering, 15(6), 458–464. https://doi.org/10.1061/(asce)he.1943-5584.0000138

Simmons, M. J., Gardiner, B. G., Windhager, S., & Tinsley, J. (2008). Green roofs are not created equal: the hydrologic and thermal performance of six different extensive green roofs and reflective and non-reflective roofs in a sub-tropical climate. Urban Ecosystems, 11(4), 339–348. https://doi.org/10.1007/s11252-008-0069-4

Solinst Canada Ltd. Barometrically Compensated Water Level Data. Solinst Canada Ltd. https://www.solinst.com/products/dataloggers-and-telemetry/3001-levelogger-series/levelogger/datasheet/barometric-compensation.php. Accessed 17 Nov. 2022.

Sproul, J., Wan, M. P., Mandel, B. R., & Rosenfeld, A. H. (2014). Economic comparison of white, green, and black flat roofs in the United States. Energy and Buildings, 71, 20–27. https://doi.org/10.1016/j.enbuild.2013.11.058

Stewart, C. (2009). "Thinking Above the Box: Green Roof History and Systems." University of Tennessee - Ut Extension.

Talebi, A., Bagg, S., Sleep, B. E., & O'Carroll, D. M. (2019). Water retention performance of green roof technology: A comparison of canadian climates. Ecological Engineering, 126, 1–15. https://doi.org/10.1016/j.ecoleng.2018.10.006

UDFCD. (2010). Urban Storm Drainage Criteria Manual; Volume 3, Stormwater Best Management Practices. Urban Drainage and Flood Control District.

U.S. Census Bureau (2021). Quick Facts: Denver City and County, Colorado. https://www.census.gov/quickfacts/fact/table/denvercitycolorado,denvercountycolorado/PST045219. Accessed on 28/11/2021

USEPA. (2003). Protecting Water Quality from Urban Runoff. EPA 841-F-03-003. USEPA, Washington, DC.

USBR. (2001). Water Measurement Manual. A Water Resources Technical Publication. U.S. Department of the Interior Bureau of Reclamation, Washington, DC.

VanWoert, N. D., Rowe, D. E., Andresen, J. A., Rugh, C. L., Fernandez, R. C., & Xiao, L. (2005). Green Roof Stormwater Retention. Journal of Environmental Quality, 34(3), 1036–1044. https://doi.org/10.2134/jeq2004.0364

Velazquez, L. S. (2005). Organic greenroof architecture: Sustainable design for the new millennium. Environmental quality management, 14(4), 73-85.