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Rain Rain Flush Away: Evaluating Rainwater Catchment First Flush Volumes

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RAIN RAIN FLUSH AWAY: EVALUATING RAINWATER CATCHMENT FIRST FLUSH VOLUMES

A Project Presented

by

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MAY 2021

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Abstract

Rainwater harvesting systems often include quality control systems such as a diverted first flush volume to improve the collected water quality. The first flush volume has traditionally been defined as a set volume of rain based on the first 1-2 millimeters of rain that falls on a roof. Diverting a volume of water can be seen as a waste when rainwater is a main source of potable water, sometimes leading to lack of implementation, and thus contaminating the final collected water. Understanding the variability of first flush volume required due to environmental parameters can be used to develop an optimized first flush system. This study evaluated rainwater catchment first flush volumes by assessing the rainwater quality over volume and time. To study these effects, we built a rainwater collection system on a test site in Amherst, Massachusetts. We performed a tracer study with the rainwater collection system to model the first flush volume required to wash out a dissolved contaminant. We collected four rain events using a fractionation first flush design. We measured water quality parameters in the atmospheric rain, first flush, and collection tank samples for each rain event. Our first flush samples resulted in elevated dissolved organic carbon (DOC) concentrations up to 40 mg/L, although there was high variation between the rain events. UV 254, DOC, and conductivity all trended together within each rain event, demonstrating a uniform wash off, of contaminants. Indicator bacteria up to 200 MPN/100 mL within rain event 1 and 2, indicates the need for disinfection if the water is to be potable. The high levels of DOC and SUVA characterization presented a concern for disinfection by-products (DBP) potential if the water were treated with chlorine. Higher intensity storms seem to increase roof wash-off deposition in the first flush. The majority of contaminants washed off in the first flush seemed to originate from roof wet and dry deposition, demonstrating the need for variable first flush volumes. Hydraulic parameters that affect wash-off, such as rain intensity and collection location, also led to varied first flush volumes. Considering these factors in the first flush volume required, could decrease treatment needs, system maintenance, and concern from treatment by-products.

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1. Introduction

Rainwater harvesting, long practiced around the world, has been of increasing interest globally due to initiatives around environmental sustainability, water scarcity, and stormwater runoff (Hamilton et al., 2019). The UNICEF and World Health Organization (WHO) Joint Monitoring Program, reported the number of people around the world who have access to an improved water source increased from 76% in 1990 to 90% in 2015 under the Millennial Development Goals (World Health Organization & UNICEF, 2015). Rainwater harvesting is considered an improved water source and can be used by rural or urban communities (World Health Organization & UNICEF, 2015). Rainwater harvesting systems consist of a catchment surface, such as impervious rooftops, a collection system made up of gutters and downspouts, a quality control system (could include first flush diverter, debris screens, or filters), a collection tank, and, finally, piping for water use (Campisano et al., 2017).

Although rainwater harvesting is widely encouraged in many places, there is high variability in the water quality and system designs based on climate, collection location (canopy cover, proximity to pollution), and water needs (de Kwaadsteniet et al., 2013; Hamilton et al., 2019). There is little regulation and universal recommendations on building, maintaining, and treating harvested rainwater systems.

Contamination of rainwater can originate from: 1) air wash out; 2) roof wash-off; and 3) collection system contamination (Fig 1). Air wash out occurs due to the acidic pH of rainwater that washes out airborne particles such as ash and pollution gases. Roof wash-off can transport both dry and wet deposition from the roof surface, including pathogens from animal droppings, decomposing organic matter from nearby trees and plants, and leaching of catchment material metals. Collection system contamination can occur from insufficient first flush, lack of maintenance of gutters and tank, and biofilm and organic matter buildup on tank and gutter walls (de Kwaadsteniet et al., 2013; Ghernaout & Elboughdiri, 2020).

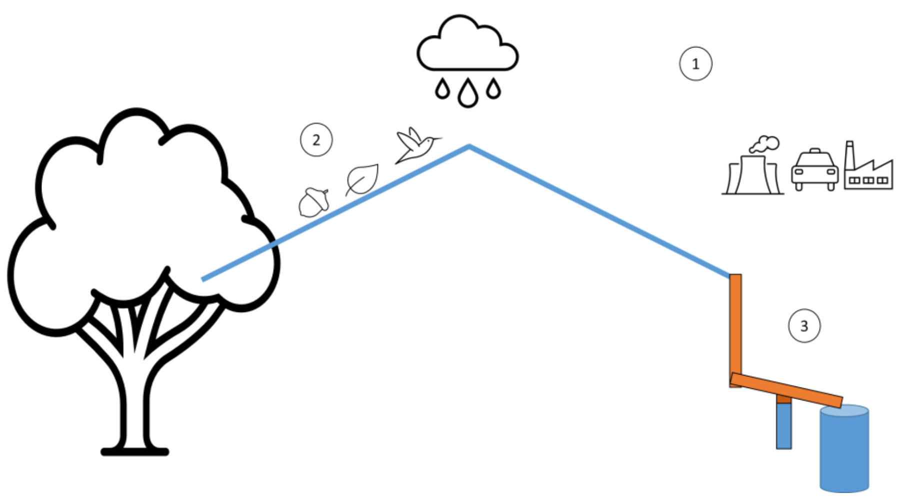


Fig 1. Rainwater Contamination Sources. 1 – air wash out from particles and pollution. 2- roof wash-out pushes out deposition on the roof surface from organic matter and animals. 3- the collection system consisting of gutters, pipes, first flush, and collection tank can add to contamination from lack of maintenance.

The purpose of first flush systems is to improve the water quality of the collected water and reduce tank maintenance by diverting the first wash of polluted water (de Kwaadsteniet et al., 2013). First flush water is often sent to waste or used for washing floors or irrigation systems. This diverted water can be seen as a waste of water when rainwater is a source for potable use, sometimes leading users to omit or bypass first flush systems. Minimizing the volume of diverted first flush water while still maintaining the water quality of the final collection tank could lead to increased acceptance and use of first flush mechanisms. It is important to understand the many parameters that affect both microbial and chemical contamination in rainwater to encourage safe water use through a sustainable system design and quality control.

Many studies recommend that first flush systems are designed to divert the first 1-2 mm of runoff, as pollutants from roof deposition are easily disturbed early in the rain event. (Campisano et al., 2017; de Kwaadsteniet et al., 2013; Kus et al., 2010). First flush systems are often geared to the removal of microbiological contaminants such as *E. coli* and Giardia lamblia, as consumption of waterborne pathogens can lead to acute health impacts. Chlorination along with a first flush system is a common and inexpensive treatment option as it inactivates many waterborne pathogens and is easy to use (de Kwaadsteniet et al., 2013). An analysis of first flush volumes in Sydney, Australia, demonstrated that the first 2 mm of rainfall allowed the final collection water to meet most of the Australian Drinking Water Guidelines, except for turbidity and lead. These levels were met by increasing the first flush to the first 5 mm.

The study also demonstrated that rainwater organic matter concentration decreased with increasing volumes of first flush (Kus et al., 2010). Organic matter in rainwater is of concern because of the potential of disinfection by-product (DBP) formation when rainwater harvesting is coupled with chlorination. Natural organic matter (NOM) can come from organics in the atmosphere such as soil and dust, as well as plants that have come in contact with the water (D. A. Reckhow et al., 1990). DBPs are compounds that form from the reaction of free chlorine with NOM. Some chlorinated DBPs that are regulated in the U.S. are trihalomethanes (THMs) and haloacetic acids (HAAs) at 80 and 60 µg/L, respectively (D. Reckhow et al., 2008). THMs have been found to be carcinogenic, causing bladder and other cancers, leading to their regulation in drinking water. Increased dissolved organic matter concentrations have been found to correlate to higher DBP formation (D. A. Reckhow et al., 1990; Richardson et al., 2007). In conventional drinking water treatment, options for minimizing DBPs in consumed water include controlling the disinfection process as well as controlling the DBP precursors in the water; in the case of rainwater, removing NOM in the first flush can decrease DBP formation potential in the collection tank.

Previous studies evaluating rainwater harvesting first flush systems tend to focus on the removal of microbiological and chemical contaminants within a defined volume to decrease potential negative health effects from use of the water for potable purposes. As chlorination is a common treatment method for the inactivation of pathogens, there is a gap in research focusing on removing NOM in first flush volumes and the parameters affecting the first flush volume required for contaminant removal. This study aims to evaluate the first flush volume needed to remove NOM, through modeling first flush volume required for roof wash out and investigating the effects of rain intensity and collection location on the first flush volume.

2. Materials and Methods

2.1. Study Site

Field experiments were conducted on the roof of the Water Energy and Technology (WET) Center located at the University of Massachusetts Amherst (UMass) in Amherst, Massachusetts (MA) at 240 Mullins Way, adjacent to the Amherst Wastewater Treatment Plant and the UMass Campus (Figure 3). Experiments were conducted from June through October 2020.

The rainwater harvesting system consisted of gutters along the west side of the roof and two downspouts. The WET Center roof is a slanted corrugated aluminum roof, with a total roof area of 1600 ft^2 (Fig 2). The southwest side of the study roof lies underneath a white pine tree, representing a canopy-covered environment during testing (Figure 3).

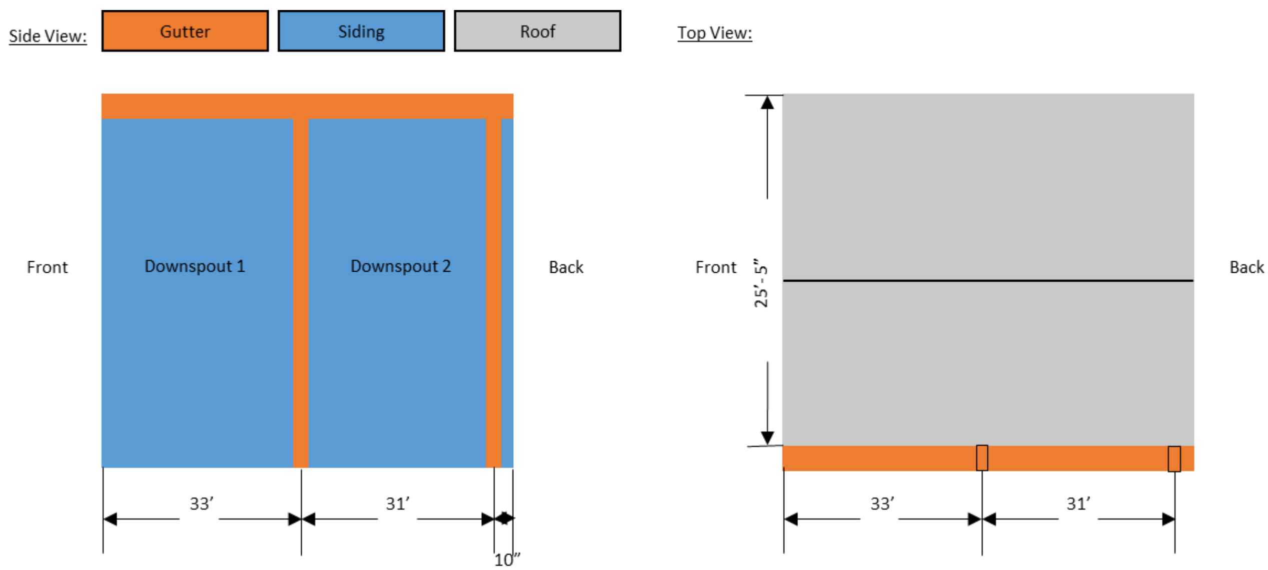


Fig 2. WET Center Roof Dimensions

a. Aerial view b. Front view c. West Side View

Figure 3. WET Center Images. a – Location of the WET Center next to the Amherst WWTP and UMass Campus. c – the test study roof lies directly underneath a possible contamination source, a white pine tree.

Precipitation data were retrieved from the Prism Climate Group at Oregon State University, which lists daily data collected from the Westover Airforce Base weather station in Chicopee, MA (*PRISM Climate Group, Oregon State U*, 2021). Amherst, MA, received an average annual precipitation of 45.2 inches from 2010-2020. Monthly precipitation averages from 2015 to 2020 are presented in Fig 4. October 2020, had the highest total precipitation of 5.8 inches during the sampling period in. Overall 2020 was a low precipitation year with June-September was classified by the U.S. Drought Monitor, as a moderate drought, and October was an extreme drought (*Amherst Conditions*, 2020).We collected on-site precipitation data from a Rainwise RainLogger 2.0 placed 10 feet from the study roof under the open sky. The rain gauge works by collecting 0.01” in a tipping bucket at a time and then counts and logs the total number of tips per rain event (RainWise forestry-suppliers.com, 2020).

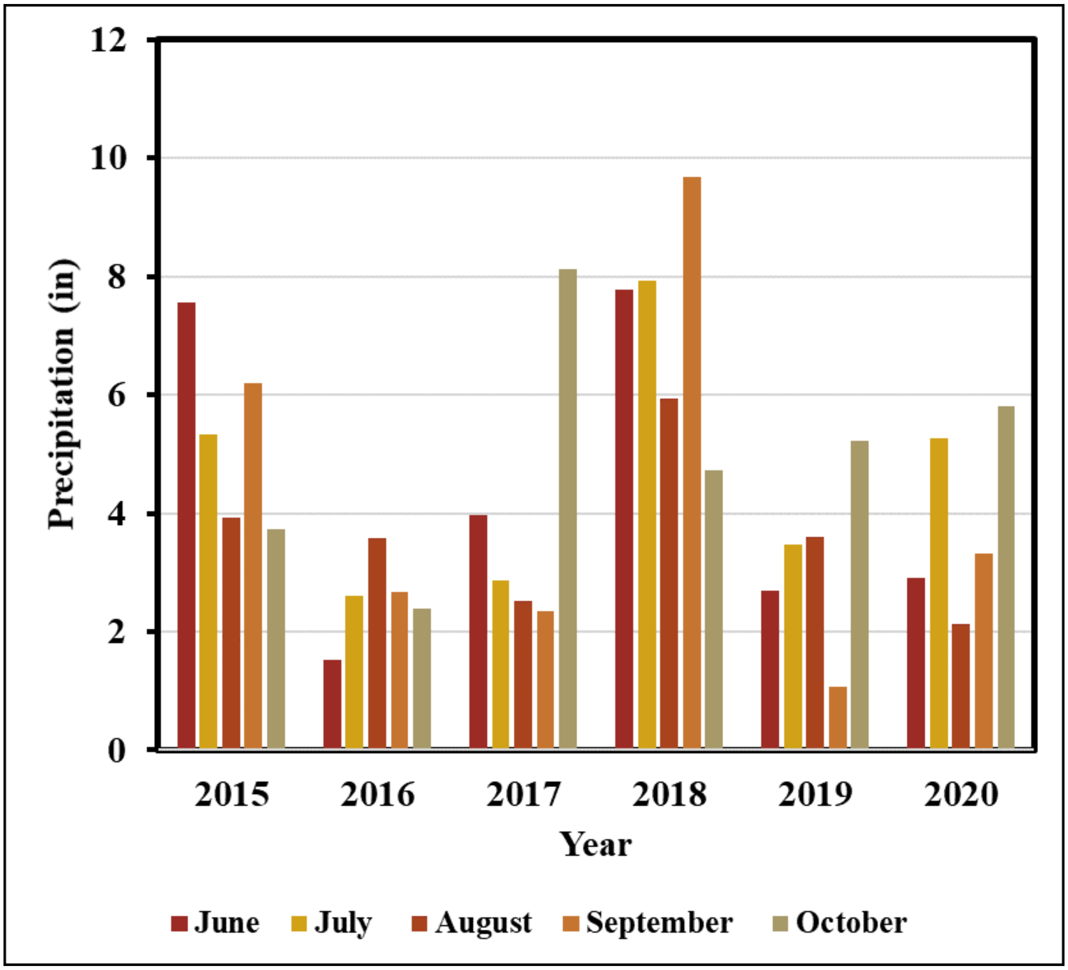


*Fig 4. Amherst Monthly Precipitation Averages from 2015-2020 (*PRISM Climate Group, Oregon State U*, 2021)*

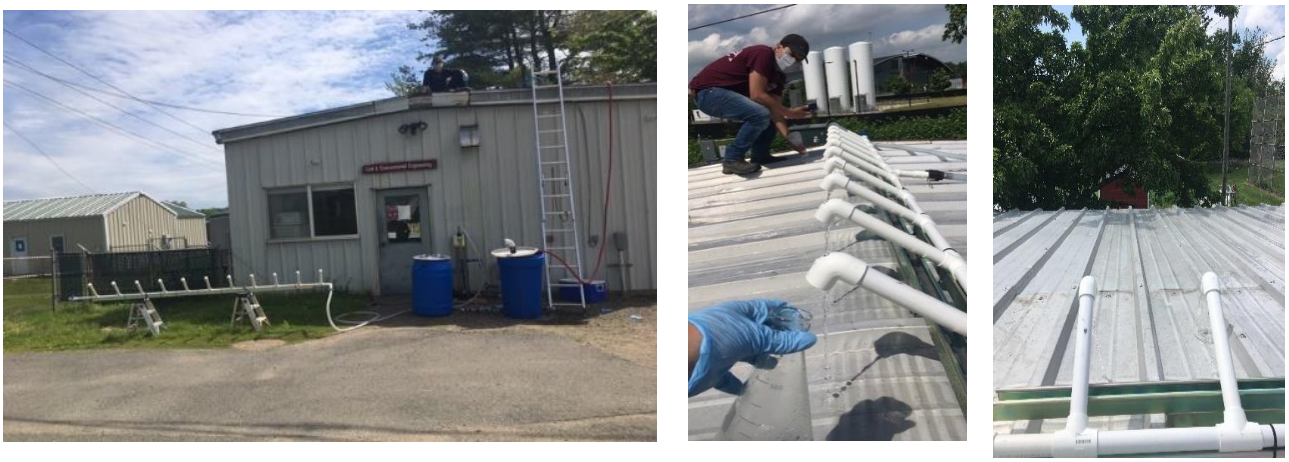
2.2. Tracer Study

2.2.1. Background

First, a study was performed on the roof to model the flow characteristics of the roof using a tracer of known concentration. The goal was to predict the first flush volume needed for the test area roof size based on the volume required to wash off the tracer. We used NaCl, which is often used as a tracer in environmental studies because it is a conservative chemical that does not degrade or react, is highly soluble, and is easily measured.

2.2.2. Experimental Setup

To simulate rain, we constructed a manifold system to pump varying flows onto the roof. We constructed a 10 ft manifold that provided flow down one side of the roof, creating a test area of 125 ft^2. The manifold consisted of a nominal 1-inch inner diameter schedule 40 PVC pipe, and 10 downspouts created by tees, and 90-degree elbow connectors on the pipe (displayed in Fig 5a, before it was placed on the roof). The 10 downspouts were placed 1 ft apart to allow flow down the center of each channel (Fig 5). The manifold was placed on an Unistrut system and connected with zip ties to keep the system in place. We cleaned the test area prior to testing using a power washer to remove external debris.



a. Manifold Design *b. Manifold Flow* *c. Roof Channels*

Fig 5. Tracer Study manifold design. a) Manifold on the ground being built; b) flow tests of each downspout conducted on the roof; c) the downspouts were centered in each channel of the roof.

The experimental setup (Fig 6) consisted of the manifold on the study roof, a pump, and two 55-gallon drums connected to the same pump with a t-connection to switch the pump flow between them. One tank contained Amherst tap water to be used as simulated rain, while the second tank was synthetic contaminated rainwater made by mixing Amherst tap water with varying doses of NaCl tracer. A pump inside the saltwater tank was used to create constant mixing. Flow reducers were used on the hose pumping up to the roof to simulate different rain intensities. Conductivity was used to measure salt concentration at the downspout of the test area using a conductivity probe. A sample port was constructed to allow for the conductivity probe to measure continuous flow, where the probe sat directly in the effluent stream with a constant overflow (Fig 7).

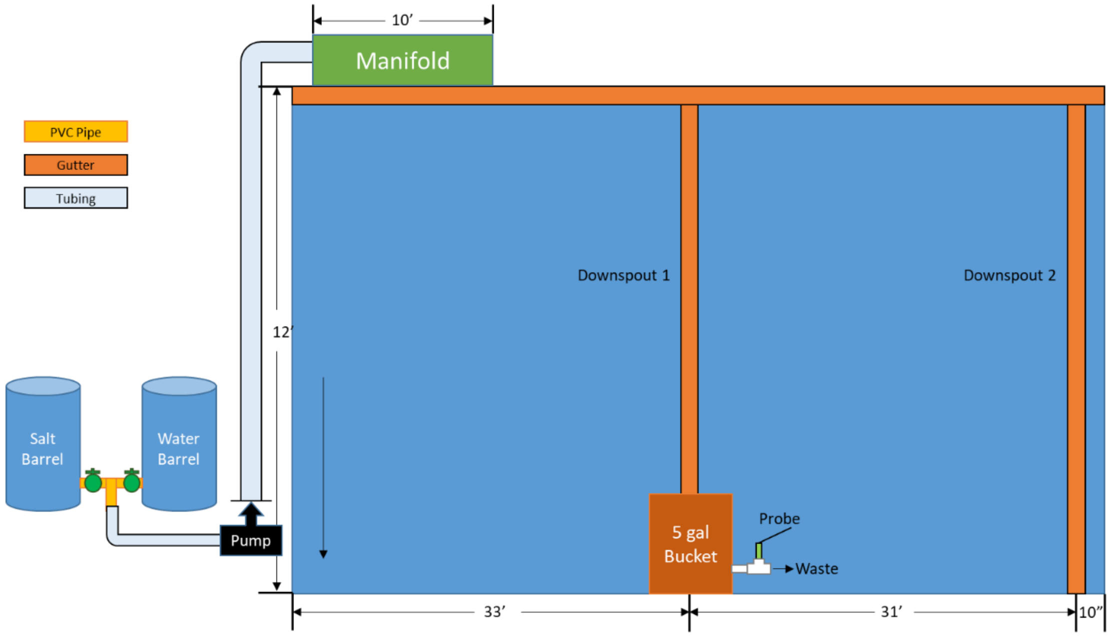
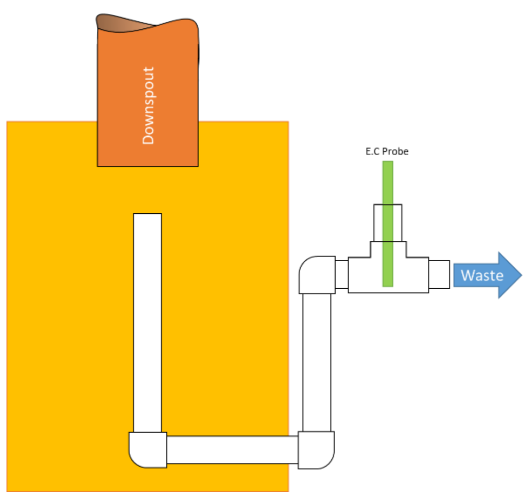


Fig 6. Tracer Study system design



a. Tracer Study Sample Port Design

b. Tracer Study Sample Port Overflow

Fig 7. Tracer Study Sample Port with the design layout (a) and the conductivity probe in a constant overflow port (b)

2.2.3. Experimental Procedure

We varied salt dose to represent changes in contaminant concentration and varied flow rates to mimic different rain intensities. Six experiments were conducted with pump flow rates varying from 4, 5, and 10 gallons per minute (gpm) and salt additions of 52, 500, and 1000 grams to the 55-gallon drum.

We first equalized the flow coming from each of the manifold downspouts by adjusting the angle of the downspout. Then we measured the time it took to fill a 1000 mL Erlenmeyer flask for each spout three times and averaged these times (Fig 5). The mean flow rate of all 10 downspouts represents the average flow rate over the roof surface in gallons per minute. These values were converted to average rain intensity (in/hr) by dividing by the test area of 125 ft^2.

Next, initial conductivity measurements were taken in the influent tap water tanks (C_0) and the saltwater tank (C). Saltwater was then pumped up onto the roof and through the manifold, with sample water channeled into the downspout. Conductivity in the effluent was measured every 30 seconds in an overflow sample port open to the atmosphere (Thermo Scientific 4-cell Conductivity). Once the effluent conductivity reached the influent conductivity (C), the influent tank valves were switched to pumping tap water onto the roof, marking the beginning of flushing. Effluent conductivity was then manually measured and recorded every 30 seconds until the conductivity reduced to the initial tap water tank conductivity (C_0). For each experiment, the test number, pump flow rate (gpm), average flow rate over roof surface (gpm), average simulated rain intensity (in/hr), and salt addition (grams) were recorded (Table 1). The time needed to lower the effluent conductivity from C to C_0 was recorded as the time need to flush out the tracer contaminant.

Table 1. Tracer Test Experiments

Test #	Pump Flow Rate (gpm)	Average Flow Rate Per Spout (gpm)	Average Simulated Rain Intensity per 125 ft^2 (in/hr)	Salt Added (NaCl) per 55 gallons (g)
1	10	1.01	0.78	52
2	10	1.02	0.79	500
3	5	0.53	0.41	500
4	4	0.45	0.35	500
5	4	0.49	0.38	1100
6	10	1.01	0.78	1000

2.3. Fractionation Experiment

2.3.1. Background

We used both the first flush estimation results from the tracer study and previously published work (Campisano et al., 2017) to inform the design for a first flush system in the fractionation method. The test area for the fractionation method was one entire side of the WET Center roof with a total area of 800 ft^2. Based on the average first flush volume result from the tracer study and the 2 mm runoff "rule of thumb" estimated first flush volume (Kus et al., 2010), we chose a first flush system of 40 gallons. We designed and implemented a fully functional first flush system at the WET Center, named the *Bois' Eau de Plui*. Our design purpose was to fractionate the first flush water to create a profile of the first wash out over both time and volume.

2.3.2. Experimental Setup

We designed our 40 gallons of first flush to be split into eight 5-gallon buckets to create a fractionated profile. Rainwater collected on the roof would flow down into the gutter system, with the middle downspout covered, and into a 2-inch inner diameter schedule 40 PVC pipe that then flowed into the five-gallon bucket first flush system (Fig 8). The five-gallon buckets were made of high-density polyethylene (HDPE) plastic. The design allows for the buckets to fill consecutively, so that once each bucket is filled the rest of the precipitation can flow over and into the 55-gallon collection tank. A vent consisting of a 2-inch pipe placed between the downspout and fractionation buckets allowed the system to depressurize before filling the buckets, thus reducing bucket lid malfunctions.

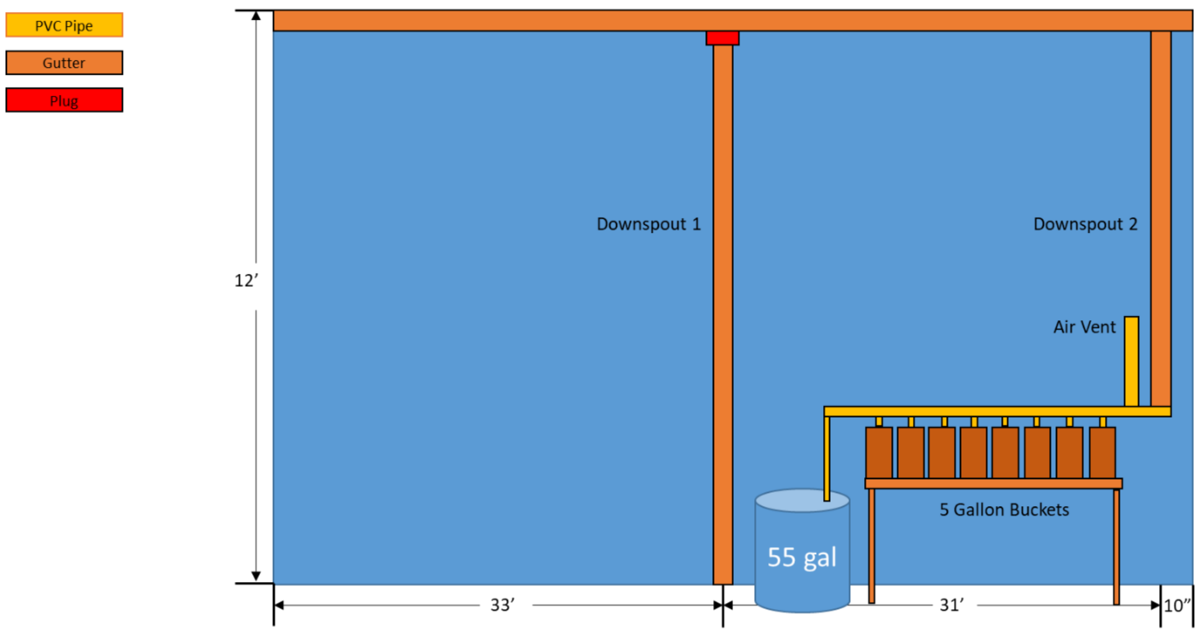


Fig 8. Fractionation Test System Design

A plastic collection bucket was placed on the study roof to collect atmospheric rainwater that did not contact the collection system. These samples are used as a control to compare contaminants that are deposited on the collection system itself. The collection system includes the WET Center roof, the gutters, piped system, first flush buckets, and the collection tank (Fig 9). Rain intensity data was collected in real-time using the Rainwise RainLogger placed 10 feet from the collection system.

a. Rain Logger

b. Fractionation Setup

Fig 9. The Fractionation Experiment included a) an onsite rain gage and b) the rainwater harvesting setup with our unique first flush design.

2.3.3. Experimental Procedure

The experimental method for each rain event allowed rainwater to flow into the collection system, with an overflow on the collection tank if more than 95 gallons were collected. Samples were collected from each fractionation bucket and the collection tank. The samples were taken in 250 mL amber jars from each fractionation bucket. Samples were collected by removing the lid and mixing the bucket with a 1-inch piece of pipe that had been cleaned with deionized water (DI) to obtain a representative sample of both dissolved and settled contaminants. The jars were placed directly in the buckets to collect the water. If the collection tank was full, two samples were taken from the collection tank: one from the top of the tank and the other from the bottom overflow valve, and reported values are an average of the two samples. We also collected an atmospheric sample from a bucket located on the roof to have a representative sample that did not touch the collection system, which we refer to subsequently as "raw" rainwater.

System maintenance after sampling included dumping and draining excess collected water from the collection system and cleaning the fractionation buckets, atmospheric sample bucket, and collection tank with DI water. The gutter was cleaned out periodically when large settlements of debris collected on top of the gutter guard by removing clumps of leaves and tree deposits.

Four precipitation events were captured. The samples from the atmospheric rain, fractionation buckets, and collection tank were compared by measuring the following water quality parameters: pH, conductivity, UV 254, and total and dissolved organic carbon. Total coliform and *E. coli* were measured in a subset of buckets. The precipitation event number, the date, and the average rain intensity are outlined in Table 2.

Table 2. Fractionation Experiments

Rain Event	Date	Average Rain Intensity (in/hr)
1	9/2/2020	0.13
2	9/10/2020	0.27
3	9/29/2020	0.02
4	10/29/2020	0.06

2.4. Canopy Method

2.4.1. Background

Following the fractionation method, we investigated the effect of the collection environment on dry and wet deposition in our collected rainwater. We accomplished this by splitting the gutter system into the two downspouts. The first downspout is at the center of the study roof and the second directly under the white pine tree. Figure 10 demonstrates the difference in deposits on the roof when looking at the area above downspout #2 (underneath the tree, left) and downspout #1 (on the right). Notably, more pine needles and organic matter are sitting on the left side of the roof.

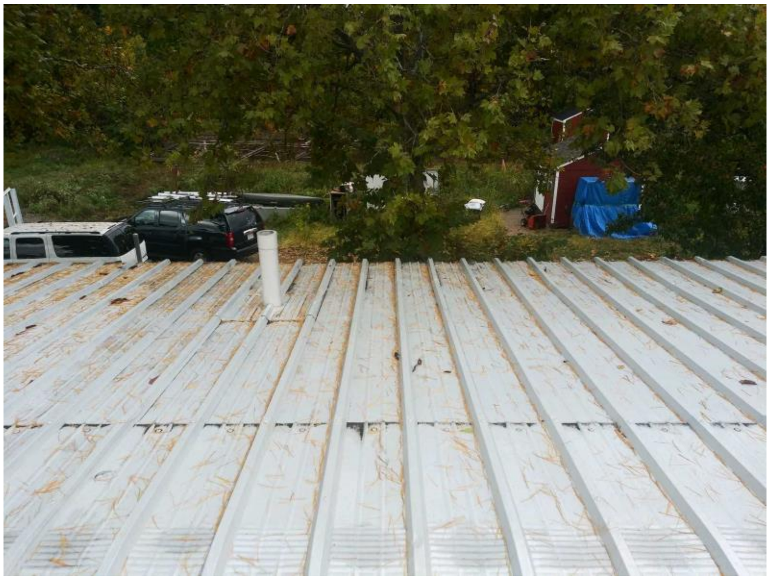


Figure 10. Roof Deposits. Pine needles and other organic matter debris can be seen on the study site roof.

2.4.2. Experimental Setup and Design

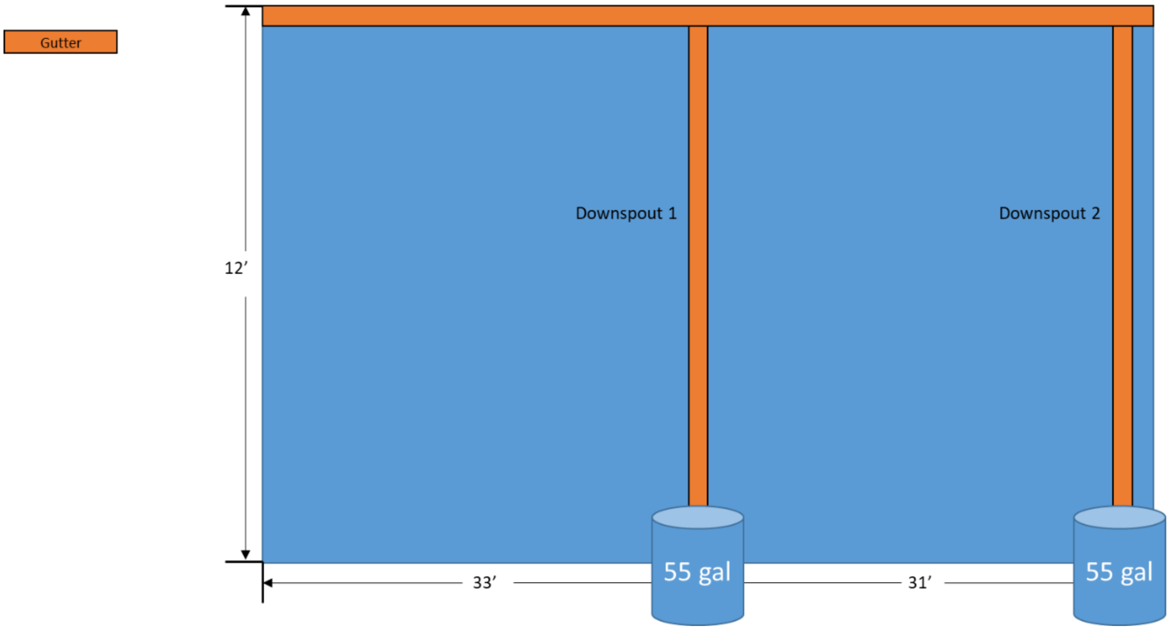


Fig 11. Canopy Design

For this experiment, we converted the gutter to PVC pipe using the downspout 2" PVC adapter and directing each downspout directly into a 55-gallon drum with an overflow port (Fig 11). We collected three precipitation events. Two 250 mL composite samples were collected from both collection tanks for each precipitation event, as well as an atmospheric rain sample. The samples from each tank were then compared to investigate canopy drip effects by measuring pH, conductivity, UV 254, and total and dissolved organic carbon.

Table 3. Canopy Experiments

Rain Event	Date	Average Rain Intensity (in/hr)
1	10/7/2020	0.22
2	10/13/2020	0.37
3	10/16/2020	0.09

2.5. Analytical Method

2.5.1. pH and Conductivity

The pH and conductivity of samples were measured immediately after sample collection in 250 mL amber bottles (fractionation and canopy method) using the Orion Star A215 pH/Conductivity Benchtop Multiparameter Meter with Atlas Scientific Lab Grade pH probe and the Thermo Scientific 4-cell Conductivity probe.

2.5.2. Natural Organic Matter Measurements

Ultraviolet absorbances at 254 nm (UV_{254}) are a surrogate measurement of NOM concentration in water. UV_{254} was measured after filtering with a 0.4 µm syringe filter on the Hach DR6000 Laboratory Spectrophotometer.

Samples were tested for total organic carbon (TOC) and dissolved organic carbon (DOC) following Standard Methods Method 5310 ("5310 Total Organic Carbon (Toc)," 2018). DOC samples were first filtered through a 0.4 µm syringe filter and then run on the Schimadzu TOC-VCPH Total Organic Carbon Analyzer. Calibration of the instrument was performed using a 10 mg/L potassium hydrogen phthalate standard and dilutions at 5, 2, 1, and 0.5 mg/L. Milli-Q ultrapure water was used for dilutions and blanks. Samples were analyzed in duplicate, with each sample having multiple injections, and the mean value was reported with a standard deviation less than 0.05.

Specific ultraviolet absorbance ($SUVA_{254}$) was calculated by dividing UV_{254} (m^{-1}) by DOC (mg/L), to give SUVA (L/ mg-m). SUVA represents the nature of NOM, with a higher SUVA representing hydrophobic NOM (SUVA >4), while a lower SUVA (<2) demonstrates hydrophilic organics. (American Water Works Association & James Edzwald, 2011)

2.5.3. Biological Activity

Total coliform and *E. coli* were tested using IDEXX Colilert Quanti-Trays 2000, to quantify the most probable number (MPN) of viable bacteria cells per 100 mL of sample. Samples were incubated at 35°C for 24 hours. The samples were collected directly from the rainwater catchment fractionation buckets, collection tank, and atmospheric plastic bucket.

3. Results

3.1 Tracer Study Results

We first calculated a mass balance of NaCl to determine if our study was representative in flushing out the tracer. The initial salt concentration in the salt tank was calculated using the recorded mass of NaCl added to the 55-gallon tank and converting to concentration (mg/L). We then calculated the amount of salt recovered by integrating the entire area under the curve in the plot of conductivity versus time for each test (Figure 13). At least 90% of the salt was recovered in the six simulated rain tests (Figure 12). In test 6 there was 110 more grams recovered than dosed, which may be due to running multiple tests in a row and excess salt from previous test being washed off.

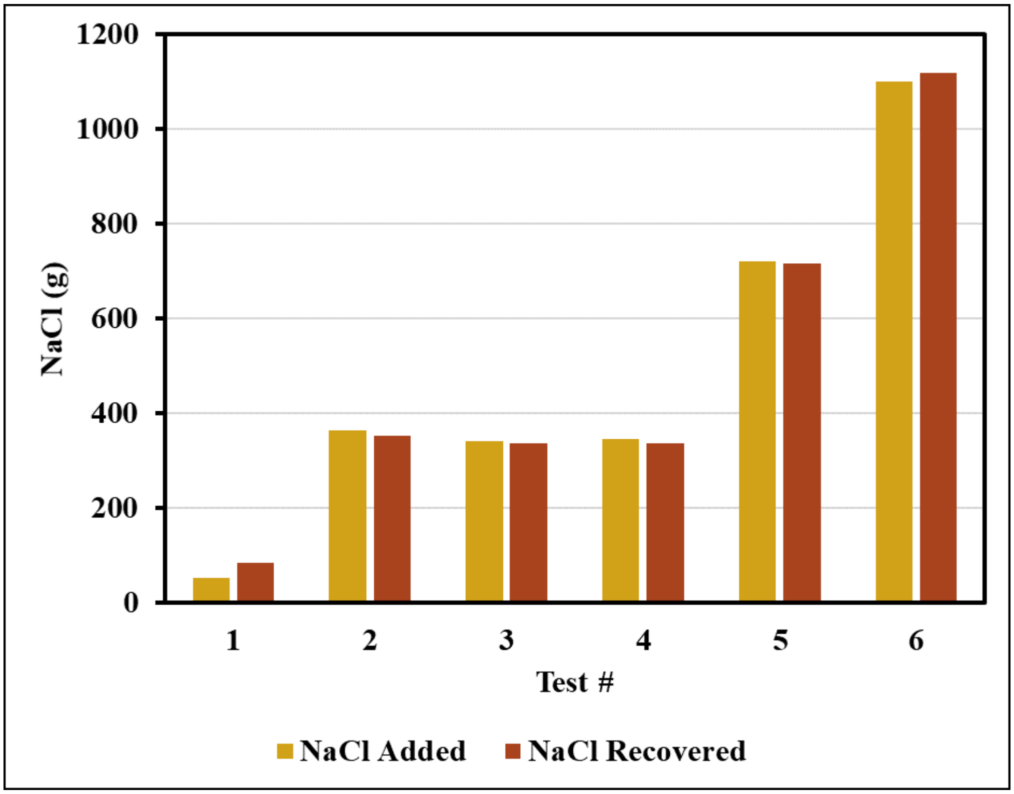


Figure 12. Tracer Study Mass Balance. The yellow columns represent the salt dosed into the influent tanks while the red columns demonstrate the mass of salt recovered based off the effluent conductivity.

The tracer study was performed to calculate an expected first flush volume needed for our study roof. We plotted conductivity versus time for each test and calculated the amount of first flush volume required based on the time to reach the tap water conductivity within 90 percent of C_0. (Figure 13).

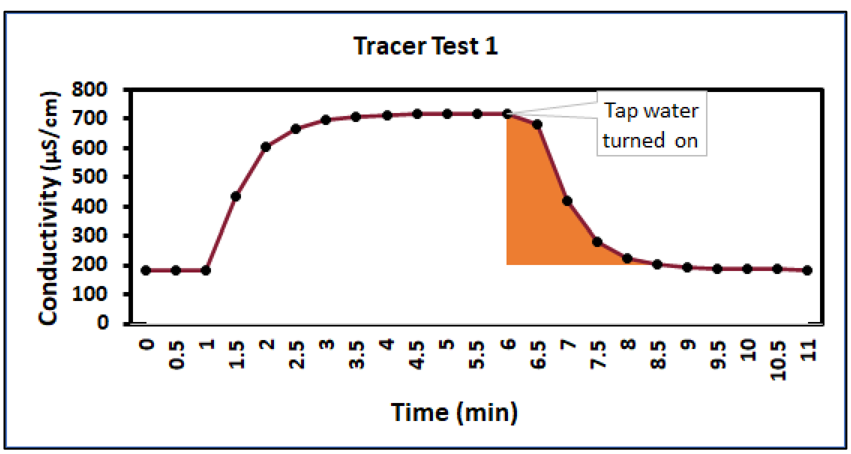


Figure 13. Tracer Test 1 Conductivity vs. Time. The shaded area is the time from when flushing with tap water began to when the conductivity stabilized to the initial conditions.

We determined the first flush volume required by integrating from the time when the tap water was turned on until initial conditions were reached (Equation 1).

$$V = (Average\ flow) \times (Time\ to\ reach\ C_0) \quad \text{(Equation 1)}$$

This volume was for the test roof area of 125 ft^2; we scaled up the calculated volume to the entire roof area of 800 ft^2 by multiplying by 6.4 to find the calculated first flush volumes required for the entire study area (Table 4).

Table 4. Tracer Study First Flush Results

Test #	Average Simulated Rain Intensity per 125 ft^2 (in/hr)	Salt Added (NaCl) per 55 gallons (g)	First Flush Volume Required (gals)
1	0.78	52	19.48
2	0.79	500	32.76
3	0.41	500	27.15
4	0.35	500	30.12
5	0.38	1000	42.27
6	0.78	1000	51.91

We investigated the effect on required first flush volumes by varying the salt concentration and rain intensities, where salt is meant to represent varying concentrations of dissolved contaminants. We compared calculated first flush volume required to salt added (Figure 14). First flush required results were proportional to increasing salt dose. We also compared rain intensity at both a low (500 grams) and a high (1100 grams) salt dose (Figure 15) and found that a lower intensity led to less required first flush volume and that, again, the volume required was proportional to increasing salt dose.

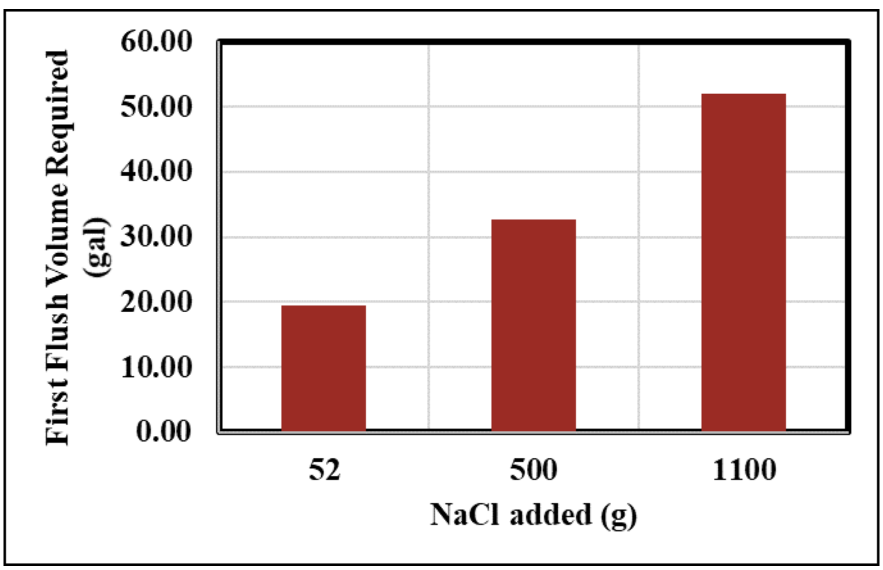


Figure 14. First Flush Volume versus Salt Addition

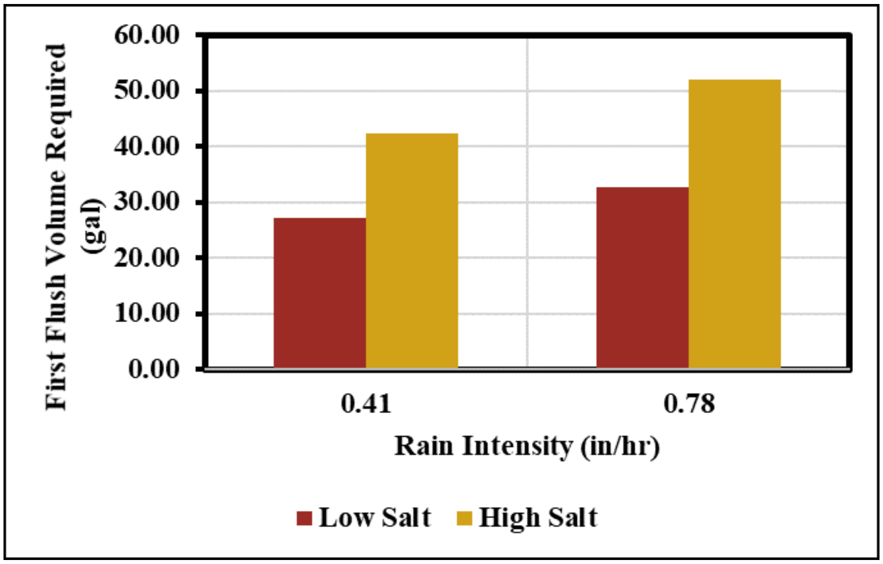


Figure 15. First Flush Volume Required versus Rain Intensity

We used the first flush volumes from the tracer study to inform our subsequent fractionation method design with an average predicted first flush volume of 33 gallons for the study area of 800 ft^2.

3.2 Fractionation Results

Four fractionation rain events were collected to evaluate the first flush volumes needed for contaminant removal. The rain intensities and dry period durations were evaluated for each measured rain event, based off the days since a rainstorm of 0.1 inches or more (Fig 16). Rain event 1 and 4 had an average rain intensity of 0.13 and 0.06 in/hour respectively and relatively short dry period. Rain event 2 had the highest rain intensity, while rain event 3 had the lowest intensity of 0.06 inches an hour and a prior dry period of 18 days (Table 5).

Table 5. Fractionation Experiments

Rain Event	Date	Average Rain Intensity (in/hr)	Dry Period Duration	Roof Maintenance
1	9/2/2020	0.13	3.00	Power washed prior to event
2	9/10/2020	0.27	6.00	None
3	9/29/2020	0.02	18.00	Gutters cleared out after event
4	10/29/2020	0.06	1.00	None

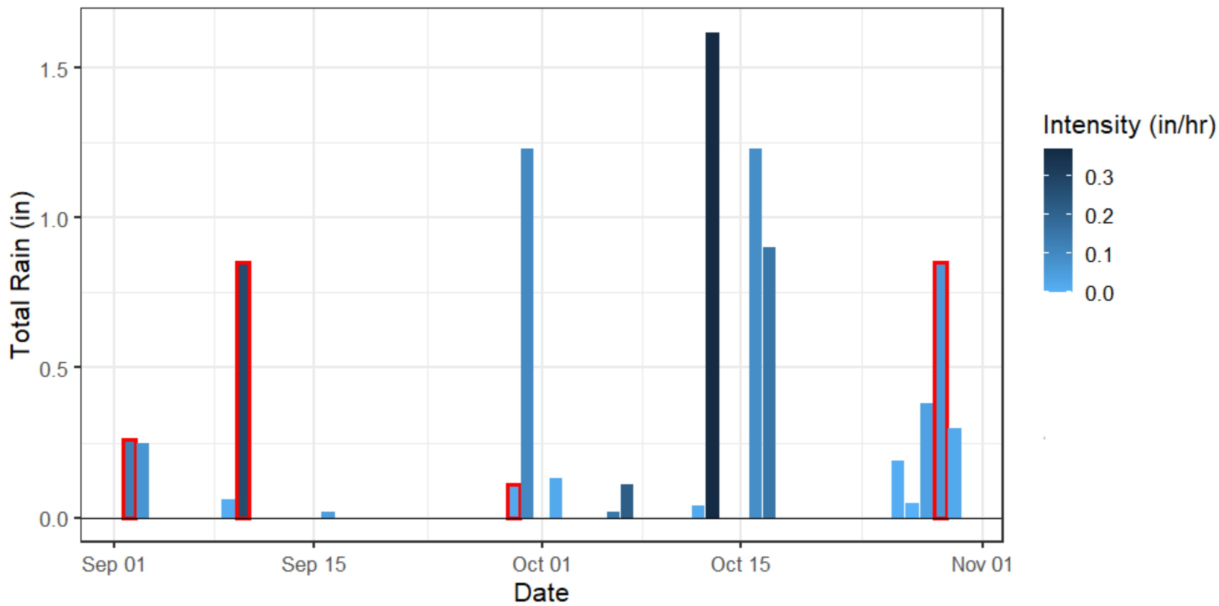


Fig 16. Rain events, rain intensity, total rain, and days since last rain. The bars represent the total rainfall in each rain event during the fractionation experiment. The blue color intensity correlates to the average rain intensity in inches/hour for each event. The four events that were collected in the fractionation experiment are outlined in red. Rain data shown was collected from the rain gauge.

To determine if our first flush volume was successful in increasing the collected water quality, we measured the conductivity, UV 254, and DOC within the fractionated first flush volume for each rain event (Fig 17).

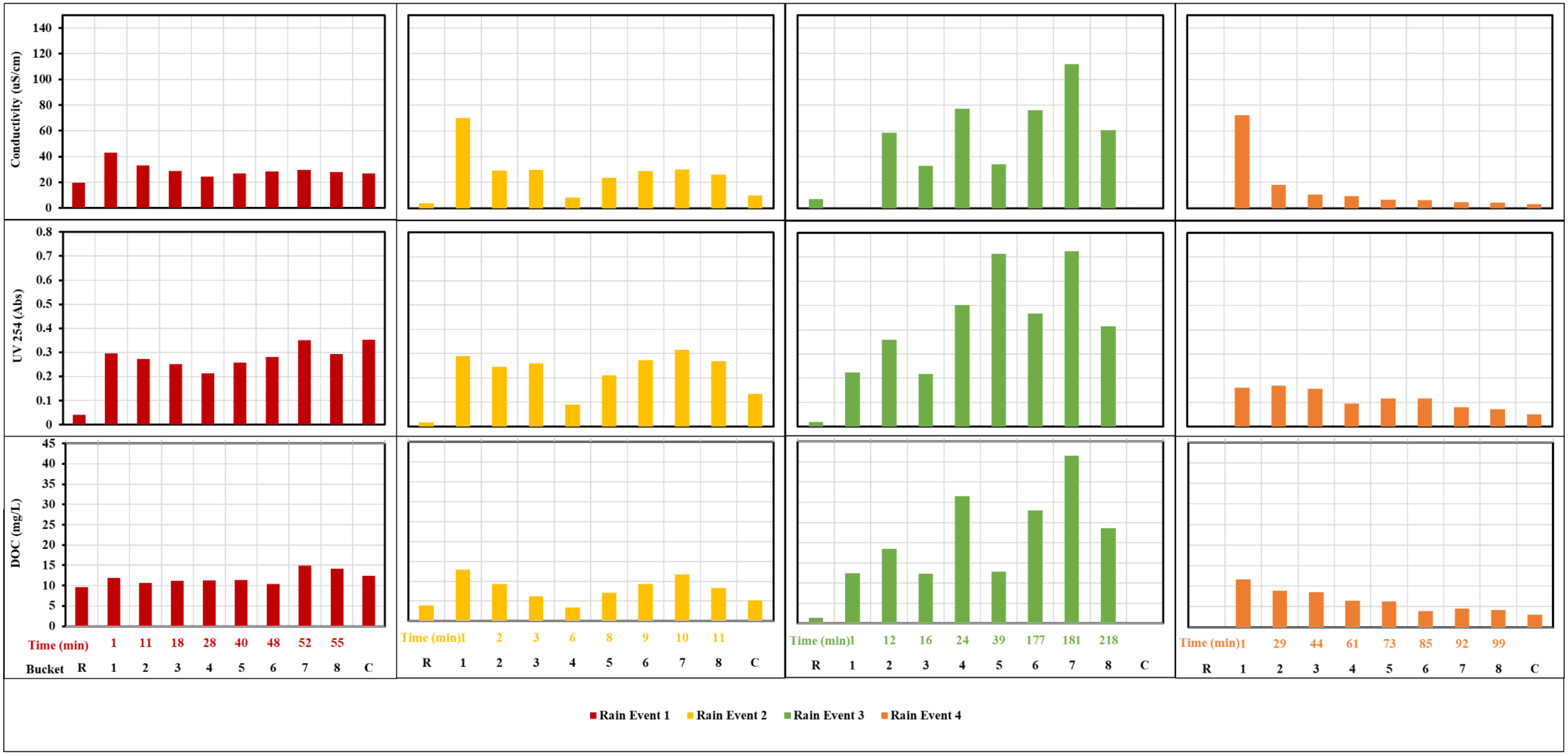


Fig 17. Fractionation results. The rows demonstrate the measurements of conductivity, UV 254, and DOC and the colors represents the unique rain events. The x-axis represents each bucket in the rainwater collection system, with R as the raw rainwater, buckets1-8 represent the first flush buckets, and C as the 55-gallon collection tank. The time it took to fill buckets 1-8 is represented on the time x-axis in minutes, with bucket 1 filling first. In rain event 3, the collection tank did not fill so no data was collected for C. In rain event 4 the raw DOC level was 0 mg/L.

The measured water quality parameters follow similar trends within each bucket within a given rain event. For example, in rain event 3, bucket 3 and 5 shows a drop in conductivity, with corresponding drops in UV 254 and DOC in the same buckets. When comparing across each of the rain events, there is a general trend where the raw water has the lowest concentrations, increasing concentrations in the first flush buckets, and decreasing concentrations in the collection tank.

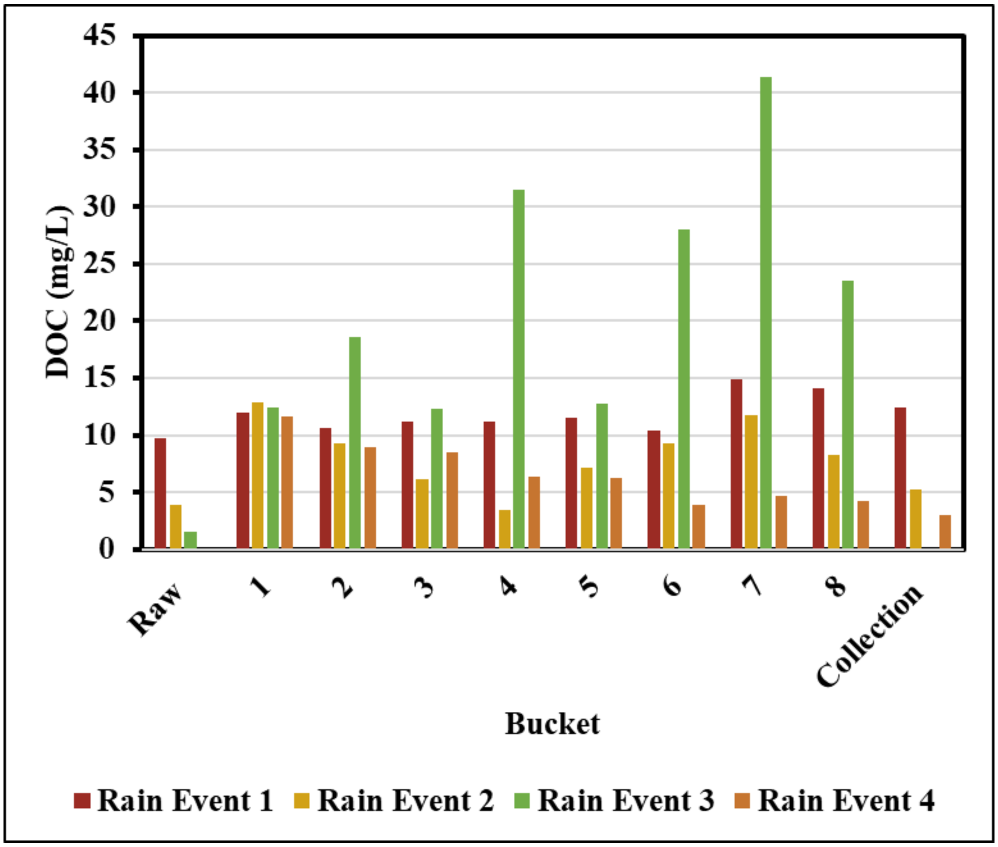


Fig 18. Fractionation of DOC. The DOC concentration across the raw rainwater, the eight first flush buckets, and the collection tank for each of the rain events.

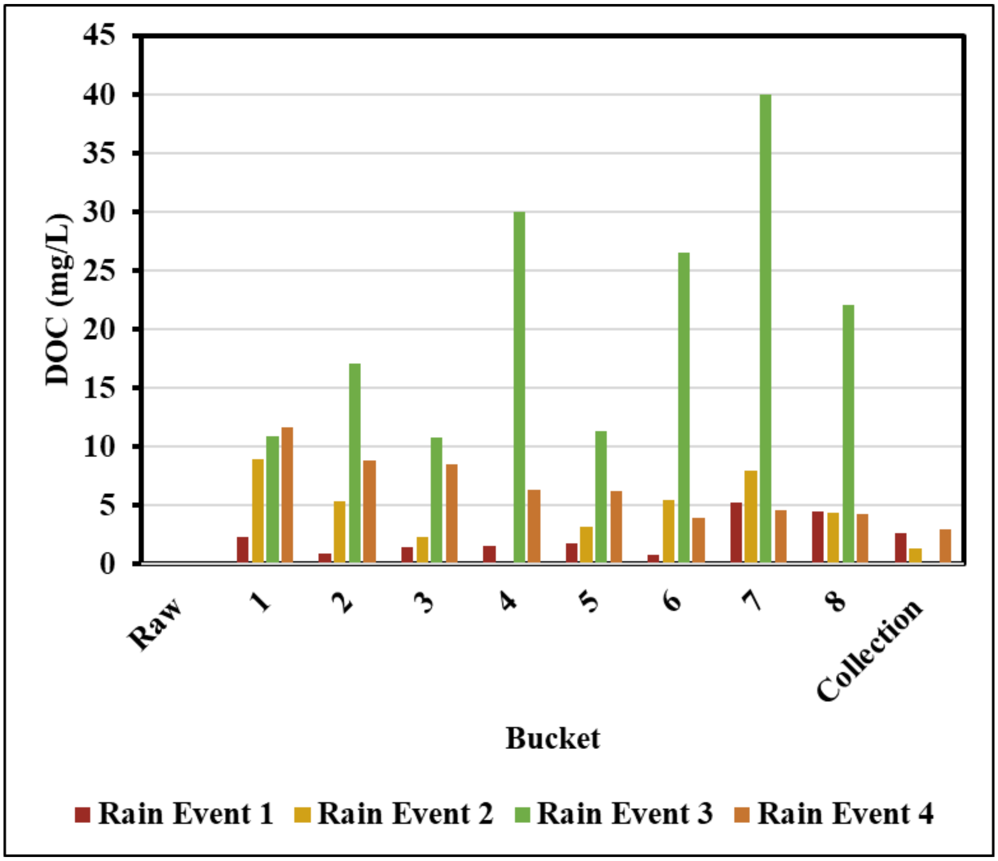


Fig 19. Fractionation of DOC deposited on the roof. These DOC concentrations were calculated by subtracting the atmospheric (raw) DOC concentration from each sample, to represent only the roof deposition DOC value.

Fig 18 shows the concentration of DOC in each rain event from the raw rainwater to the collection tank. Prior to rain event 1, the test site roof and gutters were power washed, therefore likely removing deposition. In rain event 1 the DOC throughout the first flush fractionation was consistent with the raw rainwater, demonstrating that there was little roof wash off dry or wet deposition. In Fig 19 the DOC levels were all less than 5 mg/L, demonstrating that the DOC measured in the first flush were majority atmospheric DOC.

Rain event 2 was a high intensity storm after a six-day dry period, where it did not rain more than 0.1 inches. The DOC results for this storm demonstrated that the DOC concentration increased in bucket 1 and 2 to approximately 10 mg/L, then decreased in the collection tank to 5 mg/L (still above the raw level of 3.5 mg/L). Fig 19 results suggest that roof deposition DOC likely made up the majority of measured DOC in buckets 1-3, such as in bucket 1 where the measured concentration was 12 mg/L and the roof deposition was then 9 mg/L. In bucket 4, the DOC collected was at the same concentration of the atmospheric rain, and then the roof deposition DOC concentration increased in the later buckets.

Rain event 3 was the lowest intensity storm measured and had the longest dry period of 18 days. Longer times without rain allows for roof deposition, such as pine needle debris, to build up. Rain event 3 had the highest observed concentrations of DOC, at 40 mg/L (Fig 18). The rain intensity was very low, resulting in the wash out of roof deposition likely occurring in the later buckets (7 and 8), and the collection tank did not fill the entire 55 gallons. The raw DOC concentration at 0.01 mg/L was lower than during rain event 1 and 2, but the first flush concentrations were much higher, demonstrating that DOC is likely originating from deposition in the roof and collection system, as seen when comparing Fig 18 and 19.

During rain event 4, raw rainwater had 0 mg/L of DOC, with an increase in the fractionated buckets up to 11 mg/L, and a subsequent decrease in the collection tank to 3 mg/L. This suggests that the organic matter washed off from the roof surface was concentrated in the early buckets and decreased by 8 mg/L throughout the 40 gallons of flushing.

None of the measured rain events achieved DOC levels in the collection tank matching the raw rainwater concentrations; the closest was rain event 2 where the collection tank was 1 mg/L higher than the raw rainwater.

We investigated the effect of rain intensity on the washout of DOC in the first flush by graphing the average rain intensity (interpreted from the time it took to fill each bucket) and the DOC concentration (Fig 20). The rain intensity data was collected from the onsite rain gauge that can take per-minute data by measuring how many times a 0.01-inch bucket was filled.

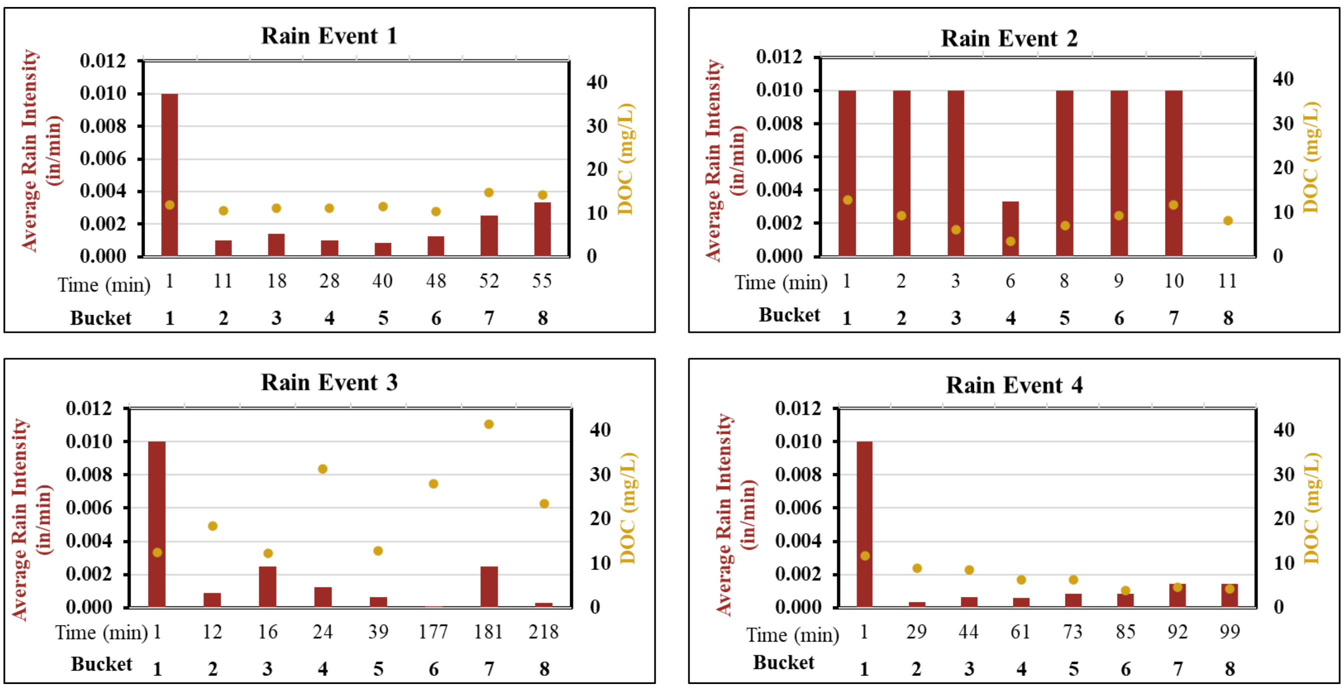


Fig 20. DOC and intensity in the first flush. These figures demonstrate the average rain intensity and DOC concentration over the time in each rain event. Each data point corresponds to the time it took to fill a fractionation bucket of 5 gallons. The bars represent the average rain intensity over the time it took to fill each bucket, while the points represent the DOC concentration (mg/L) measured in the fractionation bucket.

Rain event 1 filled the full 40 gallons of first flush after 55 minutes. Although the average rain intensity differed by bucket, the DOC concentration stayed consistent, suggesting that there little roof wash off needed to occur. Rain event 2 was a high intensity event and filled the buckets in 11 minutes. The DOC concentration decreased slightly in bucket 6 when the intensity decreased and increased again with increasing intensity. Rain event 3 had variable intensities per bucket and took 218 minutes to fill the first flush. The changes in DOC concentration per bucket did not correlate with the changes in intensity. Rain event 4 took 99 minutes to fill the first flush and demonstrated a steady decrease of DOC concentration from bucket 1 to 8, from 11 to 4 mg/L.

The DOC and intensity values for bucket 1 were similar between every rain event (approximately 11 mg/L), suggesting that the first bucket is most likely to receive DOC from a similar source such as the gutter section right next to the downspout. Comparing the four rain events in Fig 20, demonstrates that the rain intensity per bucket, does not directly affect the collected DOC concentration. When looking at the effect of the overall rain event intensity, the results demonstrate that rain event 2, the highest intensity storm at 0.27 in/hr, provided collection tank water with a DOC concentration closest to the raw water level (1.3 mg/L difference). Higher intensity rainfall may better wash out particulate contaminants such as pine needles within the first 40 gallons of first flush.

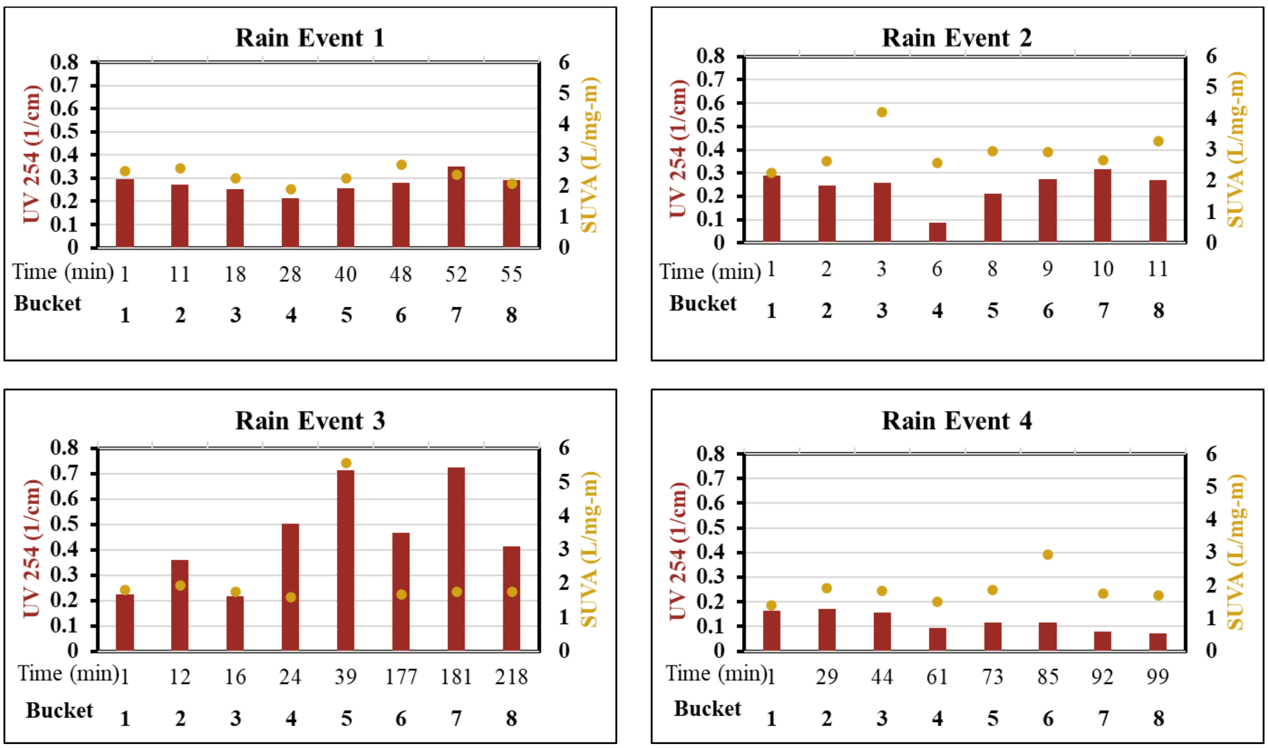


Fig 21. UV and SUVA during the first flush. The bars represent the UV 254 concentration per bucket and the points are the SUVA values over the time it took to fill each bucket.

We investigated UV 254 and SUVA values within each first flush bucket to characterize the NOM in the collected rainwater (Fig 21). The overall SUVA values were within the range of 2-4 L/mg-m with an outlier in rain event 3. Lower SUVA means the NOM is more likely hydrophilic and the range from 2-4 L/mg-m has a mixture of hydrophobic and hydrophilic NOM (American Water Works Association & James Edzwald, 2011). The EPA Guidelines for drinking water DBP states that a SUVA value greater than 4 is associated with high UV, high chlorine demand, and high THM formation potential (US EPA, 2015b). Rain event 1 had a consistent SUVA (approximately 2 L/mg-m), demonstrating that the NOM was likely atmospheric. During rain event 2, SUVA was in the mid-range (2-4 L/mg-m), which can be interpreted as NOM collected from a mixture of both atmospheric and roof deposition. For rain event 3, SUVA were all below 2 L/mg-m, with the outlier (6 L/mg-m) in the fifth bucket. The NOM that built up during the dry period came from both atmospheric and the collection system. Rain event 4 generally had a SUVA less than 2 L/mg-m.

In rain event 2, the SUVA increased when the intensity dropped; however, this phenomenon was not observed in rain events 3 or 4. This could be due to the irregular DOC concentrations in rain event 3 and the overall intensity of the storm event. SUVA and DOC data demonstrated that rain event 3 would have higher potential for DBP formation if chlorinated because of the quantity of DOC and the hydrophobic condition of the DBP precursors.

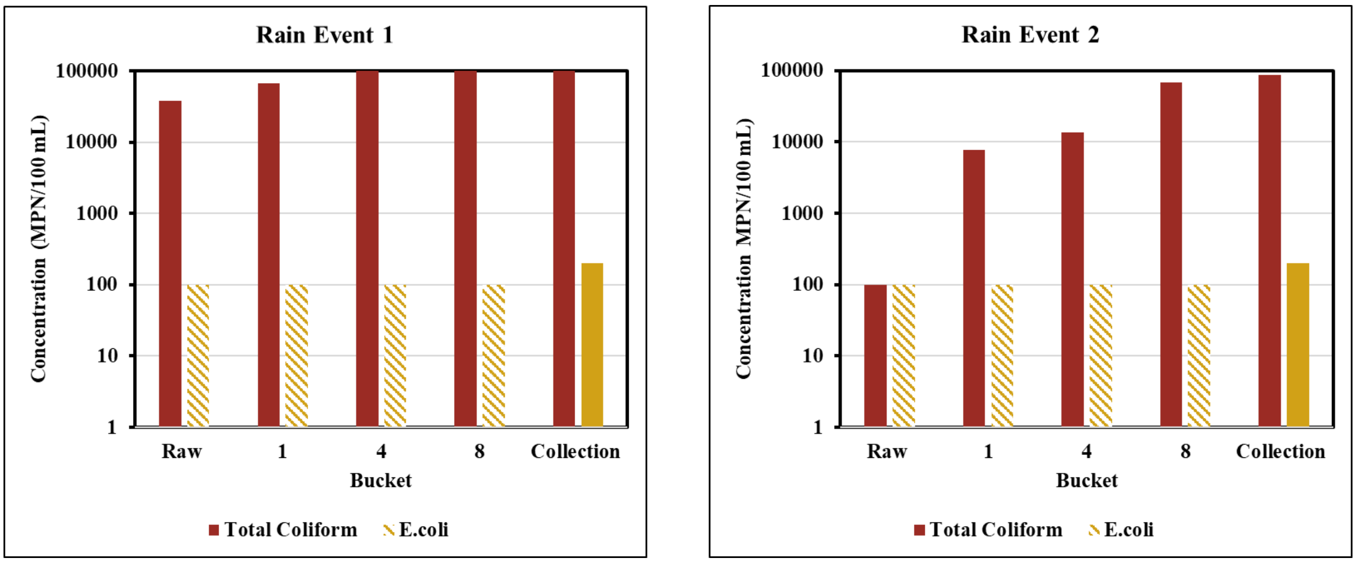


Figure 22. Total Coliform and E. coli *Fractionation Results. The fractionation of indicator bacteria is displayed on a log-10 scale. The lower method detection limit was < 100 MPN / 100 mL, thus all results reported at 100 MPN are below this value, indicated by the cross hatch.*

Indicator bacteria samples for fecal contamination were collected for rain event 1 and 2 from the raw rainwater, buckets 1,4, 8 and the collection tank. Coliforms are bacteria commonly found in soil and natural waters, while *E. coli* is more specific indicator of potential human or animal feces ((World Health Organization, 2017). Total coliform and *E. coli* concentrations are indicators of microbial quality. Their presence is source of microbial contamination or, in the case of *E.coli*, suggest the presence of pathogenic microorganisms that could cause waterborne illness. The EPA Total Coliform Rule, states that total coliform and *E.* coli maximum contaminant level goal to be 0 CFU/ 100 mL (US EPA, 2015a).

In both rain events, the *E. coli* concentration increased from the raw and first buckets to the collection tank from <100 MPN/100 mL to 200 MPN/100 mL, demonstrating that the first flush was insufficient in removing indicator bacteria from the final collected water. Contamination could have come from bucket contamination or the sample collection method, as the system was not sterilized between rain events. However, the presence of *E. coli* in the collection system demonstrates the need for disinfection in the rainwater if the water is to be used for potable use.

The simplest and most common form of disinfection of rainwater is chlorine, either through adding chlorine tablets or bleach to the collection tank (Campisano et al., 2017). The risk of adding chlorine when natural organic matter is present is the formation of DBP. Organic matter reacts with the free chlorine to create chlorinated species such as THM and HAAs. Our collected rainwater resulted in high DOC of up to 13 mg/L in the collection tank during rain event 1, and 25 mg/L in bucket 8 during rain event 3. In the EPA's 2008 report, "Long-Term Variability of NOM as Precursors in Watershed Sources", a cumulative frequency plot for the estimation of THM formation from carbon precursors in surface water, was reported (D. Reckhow et al., 2008). Using this plot and considering rainwater as a surface water and a cumulative frequency of 50% (e.g. 50% of the carbon in the water would react with chlorine to produce THMs), we estimated that the specific THM concentration in our water would be 25 µg of THMs per 1 mg of carbon. This assumes that chlorine dosing would align with a simulated distribution system. Using this estimation, THM concentrations could be up to 300 µg/L in rain event 1 and 600 µg/L in rain event 3, both exceeding the EPA regulation of 80 µg/L. This is a rough estimate, as rainwater differs in makeup compared to surface water. The average pH in measured rainwater was around 5.5, while a simulated distribution system would be 7.5-8.5. Future tests directly measuring THM formation potential in rainwater samples could confirm this estimation.

4.1 Canopy Drip

After measuring high concentrations of DOC in our fractionation experiment, we investigated the source of the NOM in our collected rainwater. After splitting our collection system into two separate downspouts collected from the two different roof areas (one under the white pine tree, and one not), we collected composite samples from two collection tanks, one directly under canopy drip of the white pine tree and the other under open sky. Three events were collected with varying rain intensities (Table 6). The difference between the roof depositions can be seen in Figure 23, where the south side of the roof underneath the white pine (left) had a much higher concentration of pine needles on the roof surface and on the gutter guard.

Table 6. Canopy Rain Events

Rain Event	Date	Average Rain Intensity (in/hr)
1	10/7/2020	0.22
2	10/13/2020	0.37
3	10/16/2020	0.09

Figure 23. Canopy Roof Conditions. The figure on the right shows the gutter guard removed on a section for the photo, to see the pine needles that passed through.

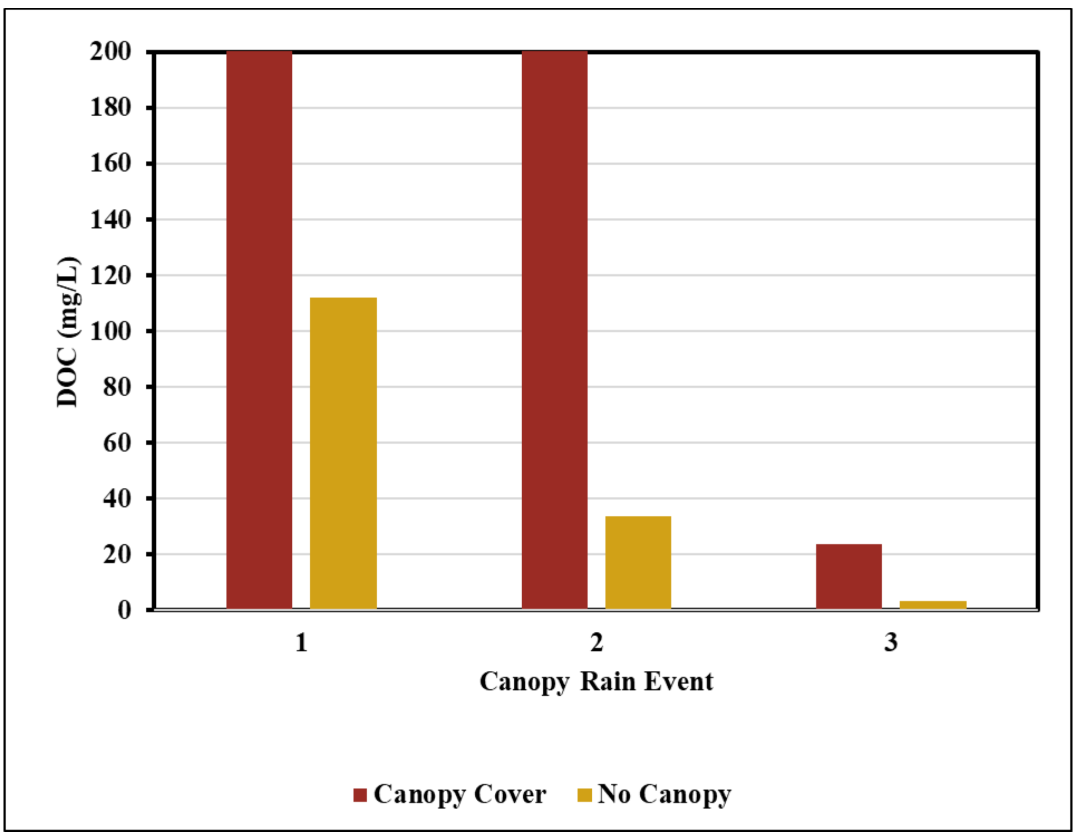


Figure 24. Canopy Drip DOC results.

The DOC concentrations measured in water from the collection tank under the tree resulted in up to six times the concentration of DOC. Additionally, the gutter under the white pine clogged, potentially leading to more stagnant water and increasing the time for leaching

NOM, increasing the DOC concentration. Since our fractionation experiment was set up directly under the canopy, it is likely that the water collected in the first flush was represented of the concentrated NOM water under the white pine, as it was closest to the downspout. Future work could perform the fractionation experiment on the non-canopy side of the roof, to measure whether the NOM concentrated water would be delayed in the collection. These results demonstrate that the location of a rainwater harvesting system should likely account for canopy drip, and ideally a roof not directed covered by a tree.

4. Discussion

The tracer study was conducted to inform the first flush volume required for the test study roof. Our results from the NaCl tracer in a test area of 125 ft^2 resulted in an average first flush volume required of 33 gallons for the entire 800 ft^2 study roof. We also found that increasing the tracer salt dose was directly proportional to the first flush volume required, the greater the salt dose, the more volume required. This aligns with the study conducted in Australia where rainwater organic matter decreased in the collection tank when first flushed volume increased (Kus et al., 2010). Lower simulated rain intensity was related to a smaller required first flush volume, likely due to a longer contact time of the water and contaminants on the roof. In this study we were modeling an ideal, dissolved contaminant with a freshly cleaned roof. This study did not consider the variability of air wash out, roof wash off, and buildup of deposition from dry periods. It did, however, result in an average volume requirement of 33 gallons, similar to the "2mm rule" (40 gallon) estimate in the literature, based on the idea that most particles are washed off in the beginning of the storm runoff (Campisano et al., 2017; de Kwaadsteniet et al., 2013; Kus et al., 2010). Although this tracer study method provided a baseline, we later found that most contaminants originate from roof deposition and not the raw rainwater itself. Future work could test this theory by conducting a tracer study by scattering the NaCl on the roof to model roof wash off.

The fractionation experiment was designed based on the tracer study results and the 2mm runoff guideline and was designed as a first flush system with a capacity of 40 gallons for our 800 ft^2 collection site. Our four collected rain events demonstrated that the first flush was successful in diverting concentrated water as the collection tank concentrations were less than the average first flush values. The 40-gallon volume was not sufficient to decrease conductivity, UV254, and DOC to the low levels of the raw rainwater. However, conductivity, UV 254 and DOC wash out all trended together within the four rain events, demonstrating a uniform wash out of roof deposition. The high concentrations of DOC in our samples due to the collection system environment may have led to an increased first flush volume required. The canopy drip experiment suggests that most of the DOC concentration was likely from the canopy and pine needle deposition from the white pine tree located directly above the downspout for the fractionation experiment. Lower intensity storms, such as rain event 3, seemed to increase the required first flush volume, although, since this storm was also after the longest dry period, we do not know if the need for higher flush volumes was due to rain intensity or time between rain events. The higher intensity storm rain event 2, resulted in collection water with a DOC concentration closest to that of the raw rainwater.

When looking at first flush volumes and the removal of DBP precursors, we did not see a reduction of UV 254 and DOC within our rainwater harvesting system. We did find high concentrations of indicator bacteria, suggesting the need for treatment such as chlorine for potable use. The concern of DBP formation with a canopy covered rainwater harvesting environment is elevated due to the higher dry deposition. Using the EPA's cumulative frequency plot for THM precursors in surface water, we estimated the potential of DBP formation upwards to 7.5 times the EPA limit for potable water, leading to a high concern of chlorination with this system. Future tests directly measuring THM formation potential in rainwater samples could confirm this estimation.

Overall, we found that the first flush volume required is variable and should not be a "one size fits all" model only dependent on collection roof size. The volume should take into consideration parameters that can lead to increase in contamination from the three categories of air wash out, roof wash-off, and collection system contamination. Our results demonstrated that most of the contamination within our first flush originated from roof wash off. This dry and wet deposition is dependent on environmental factors including nearby sources of deposition, seasonal variation, and time since previous rain. Our microbiological results could be due to both roof wash-off and collection system contamination, while this is dependent again on dry period duration, animal activity, and system maintenance. It is also important to consider parameters that affect the hydraulics of wash off such as rain intensity and collection location. Taking these factors into consideration could lead to decrease in treatment needs, system maintenance, and concern from treatment by-products as well.

One limitation of this study is that all tests were performed in the Northeast United States on the same sampling roof, leading to unique conclusions for these specific conditions. The specific contaminants of this study site, such as the white pine tree and atmospheric levels, led to the specific results. Sampling for these experiments took place from June- October 2020, with July-September classified as a moderate drought and October an extreme drought month by the U.S. Drought Monitor (*Amherst Conditions*, 2020). Due to the drought conditions, it was difficult to collect enough rain events with similar conditions. The variability in the rain events collected complicated comparisons between events. Also, the first flush volume was capped at 40 gallons, which was our estimate for washing out contaminants; however, a larger volume first flush was likely required. The collected events were primarily in the fall season, so seasonality data is lacking in our results.

Taking these results and limitations into consideration, future work on this study could include performing a tracer study to model roof-wash off volumes by spreading the solid tracer on the roof rather than dissolved. Collecting more rain events using the fractionation system, with varying intensities and seasonal variation, could help generalize trends observed in this study. Furthermore, sampling rain events with the fractionation setup under the non-canopy side would inform the hydraulics of the first flush water. Increasing the total fractionation volume to more than 40 gallons could allow for measuring whether collected water quality concentrations decreased to the raw level. Based off the estimation from this study for the high potential of DBP formation, it would be insightful to conduct experiments where rainwater samples are dosed with chlorine and THM and HAA concentrations are measured to understand their formation potential in acidic rainwater. Overall, future work could lead to a first flush volume equation that allows for the calculation of a variable first flush volume based on the parameters of rain intensity, dry period duration, location, and maintenance of the system, and the ranking of these parameters effects, to optimize the volume of first flush that needs to be diverted for each rain event or season.

5. Rainwater Catchment Experiments

We learned valuable lessons from performing rainwater dependent experiments that could be useful in future work.

- First, creating experimental controls is extremely difficult when working with the variability of rain events. Moving forward, it is recommended to develop a defined maintenance method for creating an experimental control.
    - Consistent method of cleaning the gutters before each event
    - Develop a method of categorizing roof debris
- Increase the volume of the first flush system to obtain a larger profile of air and roof wash off.
    - Increase number of buckets, or
    - Increase the size of buckets since 40 gallons was insufficient, start out with 10-gallon buckets, then decrease the volume of subsequent buckets
- Perform a dye test to map out the hydraulic route of collected water on the roof.
    - Start out by placing dye on each channel of the roof and collected both simulated rain events using the manifold and real rain events to see what water is collected in the first flush and collection tank first.
- Atmospheric collection container needs to be thoroughly cleaned immediately prior to rain collection to limit contamination.
- A remote starter if using an autosampler to collect timed samples (rain start times often differ from predictions).
- Rain predictions for both intensity and occurrence are highly varied (weather forecasts are often inaccurate). An onsite rain gauge was essential for accurate intensity data, and it is recommended to collect data with it for the entirety of a sampling period.
- It may be important to measure *E. coli* and turbidity in every collected storm, which are useful for direct public health applications. It also may be useful to directly measure metals and DBPs concentrations.
- Novel rainwater harvesting technology ideas could include:
    - Wire gutter guards with a tiny gap between the roof and the gutter guard to only allow the flow of water and not pine needles, or
    - Green roof first flush system that is connected to radar that adjusts first flush volume by shutting off a valve to diverted tank based off rain intensity and dry period duration data

6. Conclusion

The goal of rainwater first flush systems is to divert the concentrated water from the final collection tank. This study aimed to evaluate the effects of rain intensity, dry period duration, and collection location to determine if first flush volumes can be catered to specific conditions, to encourage implementation. The results demonstrated that the predicted 40 gallons of first flush for the 800 ft^2 roof was insufficient to wash out the deposited NOM from the collection surface and ensure that water collected for use resembled the water quality observed in atmospheric rain. A decreased rain intensity and increased dry period resulted in increased DOC levels in the first flush. These high levels of DOC are a concern when considering chlorination for a possible treatment method due to likely DBP formation. Other alternatives for disinfecting rainwater containing high organic matter are boiling water or UV disinfection. This study demonstrates that a rainwater collection system design should be dictated by the specific characteristics of both atmospheric rainwater and collection system deposition. In our case, the collection system was located under a canopy drip which requires that the first flush system focus on removing roof wash-off contamination. A rainwater system in an area of high air pollution would need to focus more on an air washout design and pH control. Understanding the mechanisms that affect contamination within collected rainwater could lead to optimized first flush systems, reducing the overall treatment needs and maintenance of this system, while providing quality potable water.

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