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Variation in green roof storage capacity, associated drivers, and implications for stormwater management in Portland, Oregon

By:

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An undergraduate honors thesis submitted in partial fulfillment

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Thesis Advisor

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Abstract

Greens roofs, also known as ecoroofs or living roofs, provide numerous ecosystem services and are becoming widely integrated into urban stormwater management systems. Despite a long and robust history of green roof projects in Portland, Oregon, there is a distinct lack of research on *in situ* performance. This thesis addressed this gap by investigating the hydrologic performance of five green roofs in Portland for a time period spanning November through February. Despite difficulty with the sensor calibrations, our analysis of moisture content data from these roofs revealed variation in: (1) total evapotranspiration, which serves as a proxy for total stormwater retention, and (2) storage capacity, which was defined as the difference between average maximum and minimum substrate volumetric water content measured under field conditions. Evapotranspiration was predicted by storage capacity following first order growth using non-linear regression analysis, suggesting that increasing storage capacity should correspond with increases in evapotranspiration and retention up until an inflection point of possibly 8-9mm beyond which the effect diminishes. Storage capacity was further shown to be correlated with substrate properties such as organic matter content and coefficient of curvature. Finally, retention values of 13.4% - 32.8% for Portland's rainy season in 2015-2016 were found to be substantially lower than optimal annual values reported in other studies in Portland as well as cities around the world. This suggests that Portland's green roofs may not perform as well as expected during months of high precipitation, which are the times when hydrologic performance is most critical. Further research should consider seasonal green roof performance in the Pacific Northwest and also revisit storage capacity as a parameter to include in future design standards.

Table of Contents

1. Introduction & Background

1.1 Green roof incentives

Portland, Oregon is internationally recognized for its implementation of sustainable technology for mitigating urban sources of pollution (*Sustainable Cities Institute* 2014). One of the largest sources of such pollution is contaminated stormwater runoff that occurs as a result of increased impervious surfaces. Stormwater runoff in a city stresses stormwater drainage systems and contributes to watershed pollution (Jarrett 2014). One of the ways Portland is addressing this issue is through its early and widespread adoption of green roofs - also referred to as "living" or "eco-" roofs. The City of Portland recognized green roofs as a best management practice (BMP) and Low Impact Development (LID) approach for reducing stormwater runoff on public and private property in 1999. In 2005, the Portland City Council changed the zoning code to allow green roofs as a Floor Area Ratio (FAR) Bonus, and in 2008 they set a new precedent by being the first major US city to offer a direct green roof incentive program (City of Portland, *Cost Benefit Evaluation of Ecoroofs* 2008). Green roofs are currently being considered as a requirement in the 2035 central city plan (City of Portland, *Central City 2035* 2016).

There are numerous motives for installing a green roof. They are able to provide passive building insulation (Spolek 2008), mitigate the urban heat island effect (Moody & Sailor 2013), return habitats to birds and pollinators (Kadas 2006), and offer a more aesthetically pleasing urban landscape (Lee *et al.* 2014). However, a more common design goal is to mitigate the harmful effects of stormwater runoff. Green roofs can provide an at-source reduction of total runoff volume. This reduction can also attenuate and delay the peak runoff volume, which can lessen the potential for a combined sewer overflow, or CSO (Palla *et al.* 2010; Fassman & Simcock 2012; Schroll *et al.* 2011). For instance, Palla *et al.* (2010) reports 40-80% retention of

total annual rainfall volume, and a reduction of 60-80% in peak rates of stormwater runoff for their study of a 40cm thick green roof in Italy.

1.2 Green roof design

A green roof is a multi-layer system that is used in place of a conventional, impervious roof. What makes it a "green" roof is the presence of plants living in a growing medium, also referred to as the substrate. Green roofs can be put into two different categories: extensive green roofs are low-profile, have thinner substrate depths between about two to six inches, and support drought tolerant plant species; and intensive green roofs are characterized by substrate depths above six inches that allow for more plant options but require further maintenance and produce a greater structural load (Schroll *et al.* 2011).

The plants and substrate compose the top layer of a green roof and are exposed to the outside environment (Figure 1.21). Beneath the substrate are essential layers that ensure proper and continued function of green roof performance. Directly beneath the substrate is the geotextile layer, which holds the substrate in place and prevents it from mixing with deeper components or from being washed away during a storm event. Next is the drainage layer, which often consists of a synthetic mat or granular material (such as pumice). The drainage layer allows for water to drain from the substrate and exit to runoff outlets on the roof. This function is especially important because it prevents accumulation of excess water, which can lead to plant mortality or freezing damage in cold environments (Roehr & Fassman-Beck 2015). Following the drainage layer is an integrated root barrier and waterproofing membrane. Finally, there is an insulation layer that separates the green roof system from the building roof deck. While this description of a green roof represents a typical assembly, some aspects – such as the location of the waterproofing membrane – may vary in certain designs. The many components of a green roof

and the weight of the substrate generally require the building to have a greater structural integrity to bear the additional load, when compared to a conventional roof (Roehr & Fassman-Beck 2015).
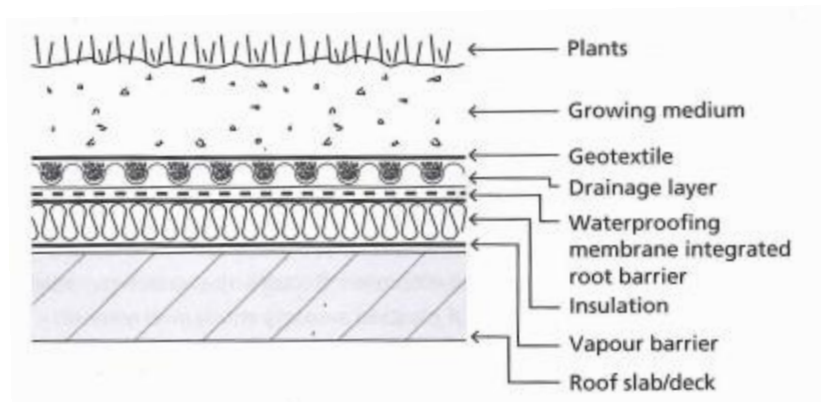

Figure 1.21: Schematic of a typical green roof configuration (Roehr & Fassman-Beck 2015)

Figure 1.22: The author on an extensive green roof in Portland, OR

The characteristics of an ideal substrate for extensive green roofs are that it is lightweight, drains easily, and provides sufficient moisture and nutrient storage for the plants of choice. As such, extensive green roof substrates are typically between 80-90% lightweight inorganic aggregate (LWA) and 10-20% organic matter (OM), by volume (Fassman & Simcock 2012). Intensive green roof substrates generally have a higher OM content and a greater bulk density in order to support the more diverse plant life (Hill *et al.* 2016).

Substrate composition has been shown to be one of the most important factors in determining the hydrologic performance of a green roof (Monterusso *et al.* 2004; Palla *et al.* 2010; Hill *et al.* 2016). There are many ways to quantify a substrate's composition. A critical design-relevant component is the overall depth of the substrate. Deeper substrates have the ability to retain more stormwater and further attenuate and delay peak runoff volume (Van Woert *et al.* 2005; Scholz-Barth 2001). Organic matter content affects the chemical and physical make-up of the substrate and has been correlated with increased maximum water holding capacity (Hill *et al.* 2016; Bot & Benites 2005). Lastly, particle size distribution - which quantifies the range of different particle sizes within the substrate - has an effect on water holding capacity (ASTM Standard D421 1998). Substrates with a uniform particle size, called poorly graded (GP), have increased air spaces between the particles, and therefore cannot hold as much water content. Substrates with an even distribution of particle sizes, called well graded (GW), fill those air spaces with smaller substrate particles, which prevent water from draining as quickly as a poorly graded substrate. Particle size distribution can be further quantified via the *uniformity coefficient,* C_u, and the *coefficient of curvature*, C_c. These two coefficients describe whether a substrate is poorly graded or well graded (ASTM Standard D421 1998).

1.3 Hydrologic performance metrics

In order to evaluate a green roof's potential for stormwater runoff mitigation, it is necessary to determine the maximum amount of water that can be stored within a substrate after a rainfall event. This measurement is known as field capacity. Another important value is wilting point, defined as the minimum amount of water that can be utilized by plants in a substrate. Water levels below the wilting point cannot be utilized by plants as increased void spaces between the substrate particles render the capillary action of the root systems ineffective. The difference between field capacity and wilting point is known as plant available water. Unfortunately, plant available water is difficult to measure for field conditions, as this requires the precise matric potential of the substrate, which incorporates thermodynamic principles in regards to the potential energy of the stored water (Tyree 2007). In this paper, we define an additional parameter that is related to plant available water: storage capacity. We define storage capacity as the maximum amount of water that can be stored within a substrate after a rain event, given the prior field conditions. This differs from field capacity in that field capacity is a theoretical maximum relative to the "dry" substrate with zero water content, a condition that is not always present in field conditions.

Storage capacity is given in terms of percent volumetric water content, or VWC (volume of water / volume of substrate), depth (millimeters of storage), and volume (cubic meters of storage). It is measured after all runoff due to gravity has occurred (Saxton *et al.* 2006). The water that is stored can be used by plants and returned to the atmosphere via transpiration, or returned directly to the atmosphere via evaporation – combined, these two terms are commonly referred to as evapotranspiration (ET). A simplified model of this water balance is illustrated in Figure 1.31.
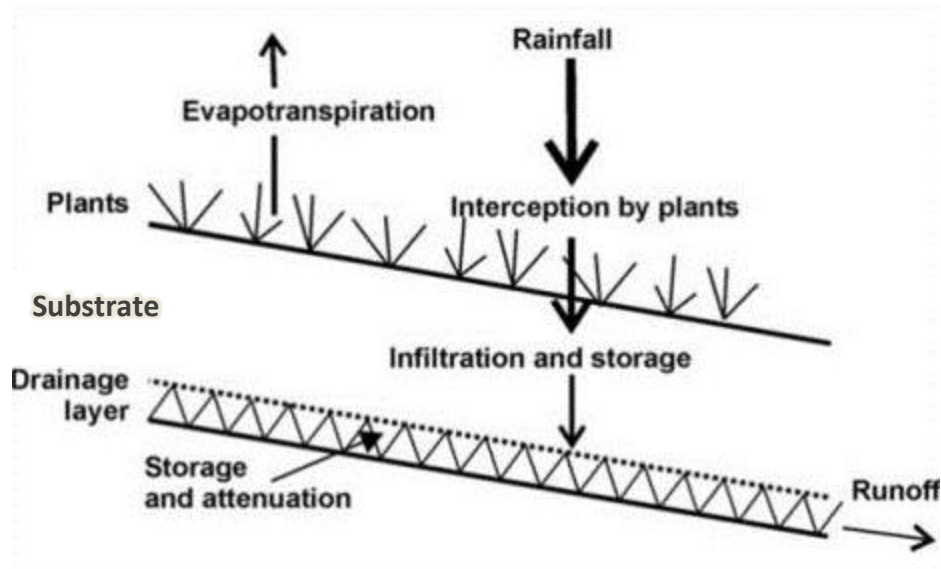
Figure 1.31: Basic water balance for a green roof (Biddulph 2013)

The ET rate of a green roof is critical to optimal performance because this process maximizes the amount of water kept in the atmospheric hydrologic cycle, thus reducing the amount of stormwater runoff (Spolek *et al.* 2008). The ideal storage capacity and rate of ET for a green roof is such that all of the water stored from a previous rain event is removed from the substrate before the next rain event. This allows for the maximum amount of rainfall to be stored again within the substrate. The effect of ET on hydrologic performance is highly dependent on the length of the dry weather period in between each rain event (Voyde *et al.* 2010). It then becomes necessary to not only understand the hydrologic dynamics of the green roof, but also the average precipitation patterns for Portland.

Figure 1.31 shows that the success of a green roof depends on both its ability to retain water as well as evapotranspire it away before the next storm. The optimal depth of storage depends on local precipitation patterns as well as anticipated rates of ET. In order to help optimize green roof design, some stormwater manuals will recommend a certain depth of storage. For example, the city of Auckland, New Zealand requires a minimum green roof depth

of 50 mm, while Toronto, Canada specifies a minimum of 100 mm (Auckland Council 2013; City of Toronto 2010). The City of Portland does not require a storage depth for green roofs, but does require other LIDs to infiltrate the 24-hour storm with a 10-year return interval, or the storm size that has a 10% chance of occurring in any given year. The manual gives this storm size as 3.4 inches, or 86.4 mm, in depth. This storm size is used as the "design storm" when discussing and comparing the hydrologic performance of the green roofs in this thesis.

1.4 Project goals

Despite the potential benefits and thorough integration of green roofs, there is a surprising lack of scholarship on *in situ* performance. Design criteria are generally taken from reference manuals such as the German Landscape, Research, Development, and Construction Society's *Guidelines for the Planning, Execution, and Upkeep of Green-Roof Sites*, known as the FLL (FLL 2008), which is an international standard for green roof design. This practice has created design standards that have not been rigorously tested and evaluated for local climate, vegetation, fauna, and other external influences. More research is needed, not only to determine the variation in *in situ* green roof performance, but also to assess the opportunity cost of different design choices in order to inform performance standards. Stormwater retention depends on substrate water storage characteristics (Fassman & Simcock 2012); therefore, storage capacity is investigated as a performance indicator. The purpose of this thesis is to address the current lack of knowledge by (1) assessing the variation in storage capacity for different green roofs in Portland and relating any variation to substrate properties, and (2) determining the relationship of these storage capacities to rates of ET as a proxy of performance.

To accomplish this goal, this thesis presents the moisture data for Portland's winter rainy season – defined as November through February, during which over half of Portland's

precipitation occurs – collected for five different green roofs in Portland. These data are used to address the following questions:

(1) How do storage capacity and rates of ET vary amongst green roofs of differing design?

(2) How might storage capacity affect total winter ET?

(3) How might substrate properties – namely, organic matter content and particle size distribution – affect storage capacity?

Due to the lack of *in situ* performance data for Portland green roofs, it was predicted that the measured green roofs will demonstrate an opportunity cost by showing variability in their storage capacities and rates of ET.

2. Methodology

2. 1 Site descriptions

Five different green roofs were selected based on accessibility and availability of moisture data. Prior to beginning this thesis work, EC-5 Volumetric Water Content (VWC) Sensors and EM50 Data Loggers from Decagon Devices, Inc. were installed on each roof in the late summer to early fall of 2015. These sensors recorded the VWC (%) of the substrate into the logger at fifteen minute intervals. As such, up to 12,000 measurements of substrate moisture data were collected for each roof over the span of Portland's rainy season (November – February).

The green roofs used in this study are located within Portland city limits, with the majority of them in the central downtown area (Figure 2.11). Three out of the five are extensive green roofs (site codes: PC, OC, and EC), with the majority of plant coverage belonging to the genus *Sedum*, while the other two (GU and CW) are intensive green roofs that had herbaceous plant coverage. Descriptions of each green roof, including substrate depth, plant coverage, age, and more, are tabulated in Table 2.11. The level of irrigation was obtained through verbal

accounts from maintenance personnel or heads of facility departments, or from observation of

the irrigation control box. Irrigation is classified as L=low, M=medium, H=high, and N=none.

However, while irrigation can be a confounding factor in the determination of hydrologic

performance, we assumed it is negligible during the time period under consideration, as green

roofs in the Portland region do not require substantial, if any, irrigation during the rainy season
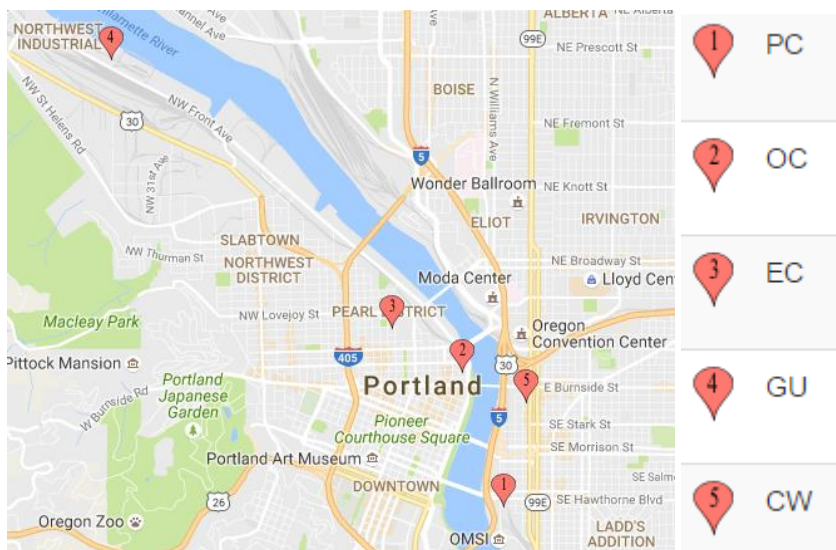
(Schroll *et al.* 2011).

Figure 2.11. Locations of green roofs used in this project (created using: mapcustomizer.com)

Site	Plant Coverage	Plant Height (cm)	Roof Area (m²)	Building Height (m)	Substrate Depth (mm)	Roof Age (yr)	Irrg. Level
PC	30%	1.59	409	14.55	116.5	4	M
OC	67%	3.42	227	15.47	87.5	4	L
EC	36%	1.78	604	12.37	82	6	H
GU	64%	15.21	194	5.26	104.5	5	L
CW	73%	14.15	1858	5.69	117	8	N

Table 2.11 Site characteristics

2.2 Substrate analysis

Particle size distribution for each substrate was determined with a sieve analysis – also called particle size analysis – following ASTM Standard D421 (1998). First, a precisely measured quantity of substrate between 200 to 500 g was obtained for each green roof. Secondly, a stack of sieves was made starting with the #200 sieve, which corresponds to a 0.075 mm mesh opening, at the bottom. Sieves were stacked such that each sieve was approximately twice as coarse as the sieve below it. The last sieve to be placed on top was the #4 sieve, which has a 4.76 mm mesh opening. The substrate was then placed on the #4 sieve and shaken for 10 minutes using a mechanical sieve shaker (Figure 2.21). The mass of substrate retained on each sieve was recorded.

Figure 2.21 Mechanical sieve shaker (https://commons.wikimedia.org/w/index.php?curid=6360346)

Figure 2.22 Sieves with variable mesh sizes used in the sieve analysis (https://commons.wikimedia.org/w/index.php?curid=650352)

A particle size distribution curve was created by plotting the percent passing (1 minus percentage of total mass retained) against the size of the sieve openings (which corresponds to the size of the substrate particles). From the particle size distribution, D_{10}, D_{30}, and D_{60} – the size of the particles at 10%, 30% and 60% passing – were determined. From these values, the

uniformity coefficient and coefficient of curvature were calculated using the following

equations:

$$(1) \quad C_u = \frac{D_{60}}{D_{10}} \qquad\qquad (2) \quad C_c = \frac{(D_{30})^2}{D_{10}*D_{60}}$$

The following guidelines for uniformity coefficient and coefficient of curvature are from

the USCS Soil Classification Chart (ASTM Standard D2487 2011). For gravel mixtures

(containing particle sizes 2.0 – 20mm, with more than 50% larger than 2.36mm), C_u>4 and

1<C_c<3 corresponds to a well graded substrate, while C_u<4 corresponds to a poorly graded

substrate. For sand mixtures (containing particle sizes 0.063 – 2.0mm, with more than 50% less

than 2.36mm), C_u>6 corresponds to a well graded substrate. The same range for C_c applies to

sand mixtures.

Substrates were also analyzed for OM content following the weight loss on ignition

method (Robertson 2013). This method gives the percent OM by weight by comparing the

weight of the substrate before and after it has been ignited in a muffle furnace. Provided that the

substrate is dry (i.e. zero water content) prior to OM analysis, the process of ignition burns off all

OM content, leaving only the mineral portion of the soil.

These substrate analyses allow for a quantitative comparison between the different green

roofs, and the results were regressed with storage capacity to determine if there was any

statistical relationship between these variables.

2.3 Sensor calibrations

The EC-5 sensors from Decagon Devices, Inc. measure VWC by a property known as

dielectric permittivity. Permittivity, given by the dielectric constant, is a measure of the

substrate's ability to hold an electric charge, and is a strong function of water (Decagon Devices,

Inc. 2015). Before the moisture data could be accurately read from the loggers, the VWC sensors

were calibrated using substrate samples from each roof. This step was necessary as green roof substrate composition can vary widely from roof to roof (Young *et al.* 2014), and this variance in composition can lead to inaccurate permittivity (and thus VWC) readings if the sensors are not properly calibrated (Cobos & Chambers 2010). By performing site-specific sensor calibrations, the accuracy can be increased from ±3-5% to ±1-2% (Cobos & Chambers 2010). These sensor calibrations allow for a mathematical relationship to be established between the raw sensor output and the actual VWC of the substrate.

The calibration protocol provided by Decagon Devices, Inc. (Cobos & Chambers 2010) was followed with a few minor changes due to the availability of resources. To begin, water was added to approximately three liters of substrate to create a "slurry" of saturated substrate. This slurry simulated the green roof substrate after a heavy rainfall event. After adding water, the slurry was mixed and left for 15 minutes to allow for the adhesion of water onto substrate particles. The slurry was then added to three 16oz cups (for replication) with holes poked in the bottom to allow for drainage of excess water (Figure 2.31). A layer of paper towels was made at the bottom of each cup to prevent any substrate particles from leaving. The three cups were then placed on a rack and excess water was allowed to drain for one hour. Following this time period, it is assumed that the remaining water is held within the substrate due to storage capacity.

After the hour drainage period had elapsed, the cups were placed in a drying oven to allow for the slow evaporation of moisture content (Figure 2.32). The same EC-5 VWC Sensors from Decagon Devices, Inc. were placed in each cup and a reading of raw probe output and millivolts were taken approximately every two hours during the day, for two to five days, until the substrate appeared visibly dry. At the time of each sensor reading, a measurement of the weight of the cup, substrate, and water content was also taken. A final measurement of raw probe output, millivolts, and weight was taken at least one week after the two-to-five day period. The

cups were left in the drying oven over this time period, and at this point were considered "oven dry" (i.e. no water content left within the substrate).

Figure 2.32. Substrate in cups with sensors placed in drying oven to allow for the evaporation of moisture content

Figure 2.31. 16oz cup with holes used for sensor calibrations

The initial mass of water in the substrate was calculated as the initial mass of substrate plus water minus the final mass of the oven-dry substrate. Using the density of water, the initial volume of water in the substrate could also be determined. From this value, the VWC at each measurement interval was calculated as the volume of water present in the substrate divided by the sum of the volume of water and the volume of soil. Ideally, the VWC should be calculated as the volume of water divided by the volume of the initial wetted substrate – which is a sum of the volumes of substrate particles, air pores, and water content (Black 1965). However, this value could not be determined given the calibration apparatus used in this study. Nevertheless, we consider the value for wetted substrate volume used here accurate enough for data comparison and analysis.

To establish the mathematical relationship between the raw sensor output and VWC, the two values were plotted against each other in Microsoft Excel (2010) for all three replicates. A calibration curve was created for each green roof using a second power polynomial trendline. These curves are provided in *Appendix A: Calibration Curves*. The resultant calibration equations were then applied to the raw sensor data using either Excel or DataTrac 3, an application from Decagon Devices, Inc. used to analyze the moisture data from their sensors. The outputs from the calibration equations are the "true" VWC readings for each green roof.

2.4 Field data analysis

Substrate storage capacity was calculated as the difference between the average maximum VWC and average minimum VWC, after the removal of all outlier data points. Outliers were found due to extended periods of freezing temperatures. Because the EC-5 sensors measure the dielectric permittivity of the substrate, freezing conditions can result in a VWC reading far below the true value (Kalorkoti & Barber 2009). Average maximum VWC was determined by averaging the maximum VWCs observed on the three days with the most rainfall out of the collection period. Similarly, average minimum VWC was taken by averaging the minimum VWCs observed after the three longest dry weather periods. Rainfall data were taken from the City of Portland HYDRA rainfall network, provided by the USGS (2016). Specifically, the rainfall data are from the Portland Fire Bureau rain gauge located at 55 SW Ash Street, as this is the gauge closest to the green roofs used in this thesis.

As precipitation falls on a green roof, it saturates the substrate until the maximum possible VWC (also known as "field capacity") is reached. Past this point, it is assumed that all additional precipitation becomes runoff, and that ponding within the substrate does not occur. Therefore, it is also assumed that all increases in moisture content reflect storage, and all losses

represent evapotranspiration. Consequently, ET was calculated as the difference between a given reading of VWC and the subsequent reading, so long as that difference was positive (i.e. moisture content decreased with time). Summing these values, with the exclusion of outliers, a total amount of ET was obtained for each green roof. Using a simplified water balance model, ET is equal to the difference between rainfall and runoff. Other studies refer to this measurement as "retention," (Palla *et al.* 2010; Spolek 2008; Hutchinson *et al.* 2003), and it is important to remember this distinction when comparing our analysis results to these studies.

Since all five green roofs vary in terms of depth and area, percent VWC does not provide an accurate comparison measure in performance. As such, depths (mm) of storage and ET were calculated by multiplying the percent VWC by the depth of the substrate. Volume (m^3) of storage and ET could then be determined by multiplying the green roof area. These storage metrics were used to evaluate each green roof's hydrologic performance potential following the Portland Stormwater Management Manual (2016) guidelines for a design storm.

3. Results

3.1 Storage capacity and evapotranspiration

The calibrated moisture data for each roof were plotted with time on the same chart (Figure 3.11). The same chart with pre-calibrated data is given in *Appendix B: Raw Data Comparison* to show the effect of calibrations on sensor readings. Figure 3.11 serves as a visual confirmation that all sensors were behaving synchronously, as they show similar trends in increasing and decreasing VWC. Furthermore, there are marked differences in the magnitude of VWC in each roof. The EC roof demonstrated the greatest average VWC, while the GU roof displayed the lowest.

Examining daily precipitation data from the HYDRA rainfall network, the longest dry weather periods occurred from November 25-29, February 6-10, and February 23-25 (Figure 3.11). Decreases in VWC were observed for each roof over these time periods, which are depicted on Figure 3.11. Average minimum VWC was calculating using the minimum VWC observed on the last day for these three longest dry weather periods.

The sharpest decrease in VWC occurred just after December 31. Upon examining daily temperature data from the National Oceanic and Atmospheric Administration, it was discovered that this was due to an ice storm that lasted from January 1-4 (NOAA 2016). Peak precipitation occurred on December 7, 8 and 17 with measured values of 69.6 mm, 59.4 mm, and 40.1 mm, respectively. Average maximum VWC was calculated for each green roof using the maximum VWC observed on these three days of peak precipitation.

Following the data analysis protocol, storage capacity was calculated from the average maximum and average minimum VWC (Table 3.11). Maximum VWC (or field capacity) observed in the lab is also compared to maximum VWC observed in the field, as a redundancy measure to check that they are in the same range. In general, the field values were similar to those measured in the lab, with all roofs having a difference of less than 10%, with the exception of the GU roof, which was 14.8% different. Interestingly, while the GU roof showed the lowest average VWC, it had the greatest storage capacity, storing 11.4% or 12.0 mm of expected rainfall. However, the GU roof had the lowest volumetric storage capacity as it covered the smallest roof area at 194 m^2 (Table 2.11). Conversely, while the CW roof did not have the highest storage capacity percentage, it did have the greatest volumetric storage capacity due to its expansive area of 1858 m^2. The OC roof had the lowest storage capacity by all metrics.
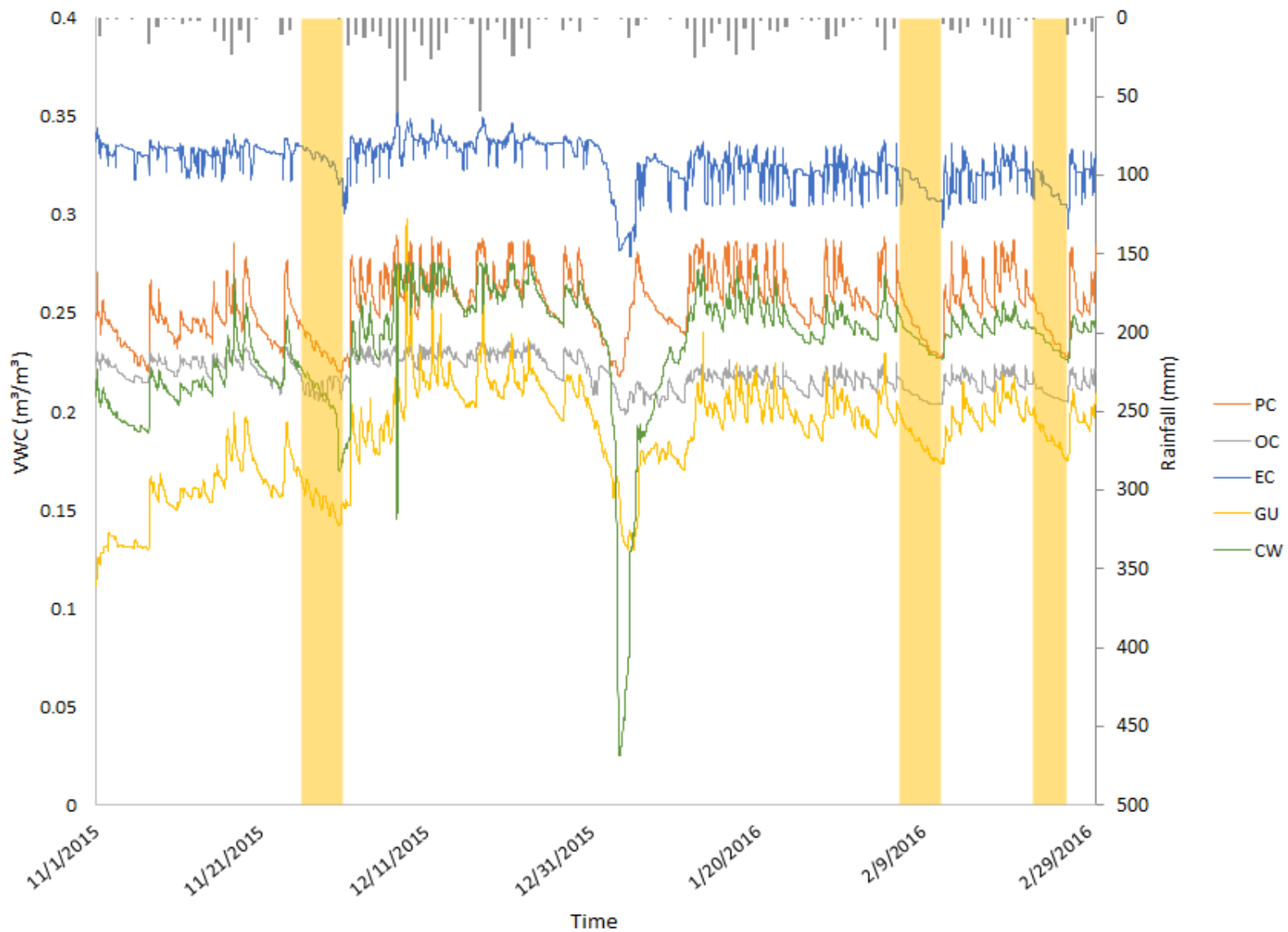
Figure 3.11. Calibrated moisture data for all five roofs over Portland's rainy season. Rainfall is represented with gray columns above, and dry weather periods are marked by transparent yellow bars

The ability of each green roof to capture the 10-year design storm is given as the percentage of the 86.4mm of rainfall depth that can be stored (Table 3.11). As rainfall intensity increases with the return interval (in this case, 10 years), it can be assumed that the measured green roofs store a greater amount of the rainfall that occurs with the more frequent, less intense storms. Nevertheless, the values in Table 3.11 must be considered when discussing urban stormwater management in Portland, as these are the guidelines given by the City of Portland's Stormwater Management Manual (2016).

| Roof | Maximum lab VWC | Maximum field VWC | Minimum field VWC | Roof area (m^2) | Storage Capacity | | | % of 10-year design storm retained | Evapotranspiration (% of total rainfall) |
					%	mm	m^3		
PC	29.3%	28.7%	22.7%	409	6.0%	6.983	2.856	8.1%	32.8%
OC	25.8%	23.5%	20.4%	227	3.1%	2.67	0.606	3.1%	13.4%
EC	34.7%	34.9%	31.2%	604	3.8%	3.082	1.862	3.6%	27.6%
GU	32.6%	28.1%	16.7%	194	11.4%	11.958	2.32	13.8%	23.9%
CW	25.8%	27.5%	21.8%	1858	5.7%	6.692	12.434	7.7%	25.1%

Table 3.11. Hydrologic performance measurements for each green roof. Maximum lab VWC is compared to field VWC, and average field maximum and minimum VWC are used to find storage capacity. Volumetric storage capacity was calculated by multiplying the roof area by the depth of storage. Total evapotranspiration as percent of total rainfall is given.

The total amount of evapotranspiration from November through February is compared between each roof (Table 3.11, Figure 3.12). The PC roof was found to have the highest ET at 304.5 mm, while the OC roof had the lowest at 124.3 mm. Using the total precipitation value of 928.6 mm (Table 7.1 in *Appendix C: Precipitation Data*), the green roofs in this study evapotranspired 13.4% - 32.8% of received rainfall over the winter months of the study. ET rates do not appear to correlate with plant coverage or height, as the PC roof had the highest ET while having the lowest plant coverage and height (Table 2.11). Regression analysis concluded that storage capacity may predict evapotranspiration following first order growth kinetics with $r^2 = 0.2477$ (Table 3.22)
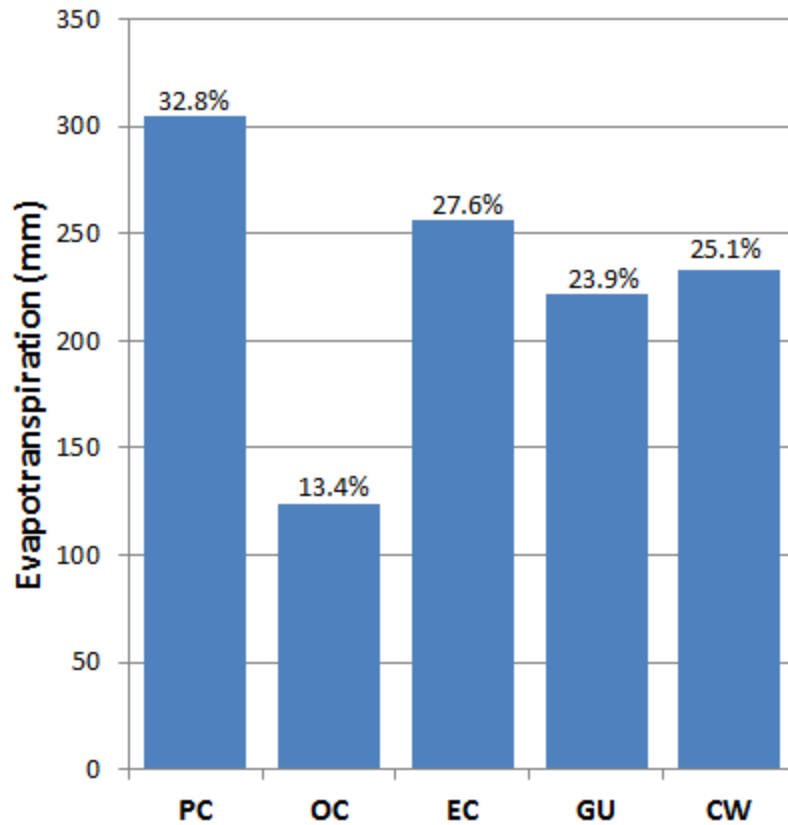
Figure 3.12. Evapotranspiration for November through February. Percentage of total rainfall converted to ET is given above each column.

3.2 Comparison of substrate characteristics

Sieve analyses of each green roof substrate were completed and the resultant particle size distributions were obtained (Figure 3.21). Each substrate fell within its guidelines for an ideal particle size distribution as described by the FLL (2008). As expected, the three extensive green roofs (PC, OC and EC), displayed similar particle size distributions. The GU roof was found to have the smallest particle sizes overall, and the particle size distribution curve was interpolated to determine D_{10}. Using D_{10}, D_{30}, and D_{60} from Figure 3.21, the uniformity coefficient, coefficient of curvature, and subsequent substrate gradation classification were found for each substrate (Table 3.21). All substrates were classified as poorly graded (GP) except for the PC roof, which was found to be well graded (GW). Organic matter content for each substrate is

presented alongside the sieve analysis results (Table 3.21). With four out of the five green roofs

having less than 10% OM, the measured OM content is low compared to most green roofs

substrates, with 10-20% OM typically seen on extensive green roofs, and higher amounts seen on

intensive green roofs. Regression analyses show that there may be a positive correlation between

coefficient of curvature and storage capacity with $r^2 = 0.400$, and a negative correlation between

OM content and storage capacity with $r^2 = 0.336$ (Table 3.22). However with p-values from 0.25-

0.3, these are not statistically significant results – this is likely due to the small sample size of

five roofs. Uniformity coefficient did not yield a statistically significant relationship.
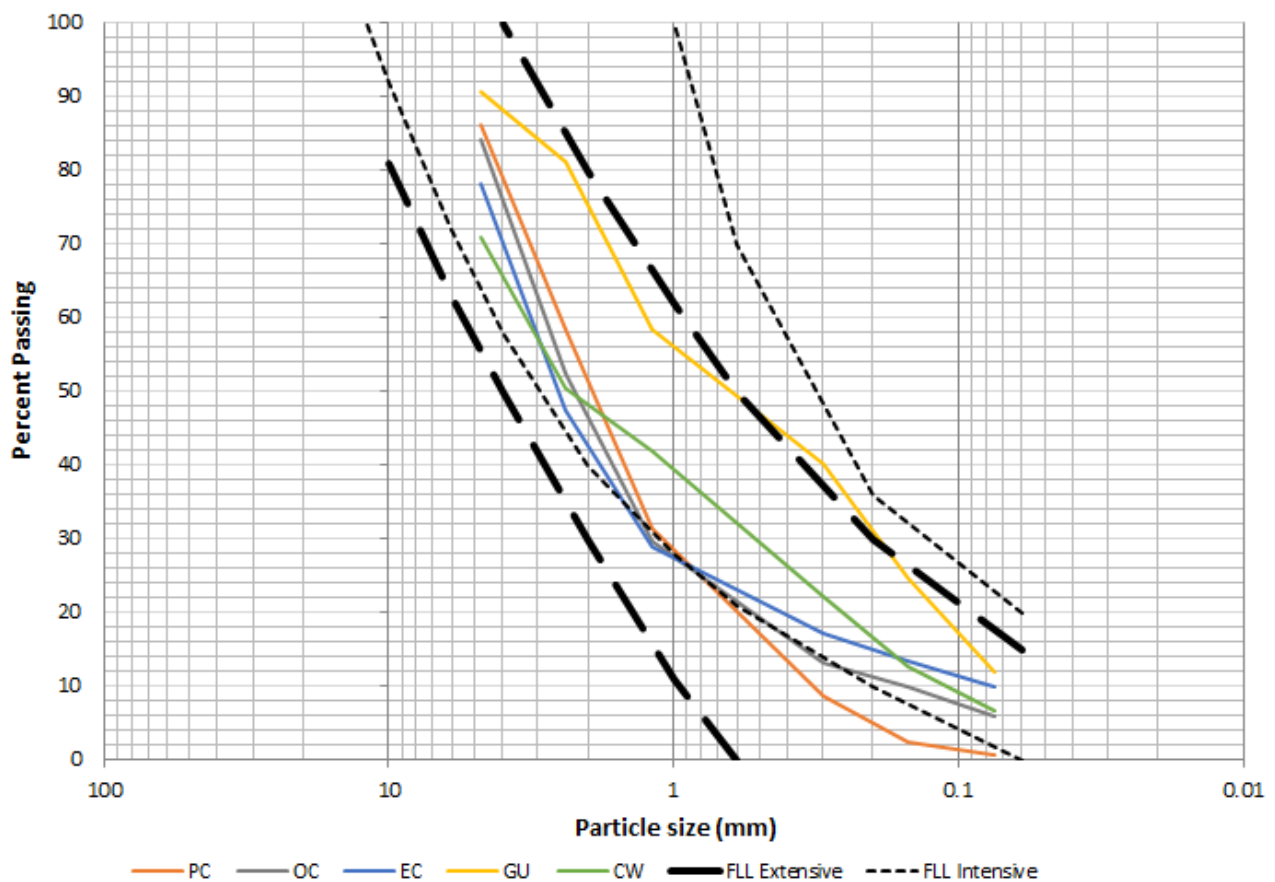

Figure 3.21 Particle size distributions for all five green roofs. The FLL guidelines for extensive green roof
substrates are given by the thick dashed lines, and intensive substrates by thin dashed lines (FLL 2008).

Roof	Uniformity coefficient	Coefficient of curvature	Substrate gradation	OM content (% by mass)
PC	7.58	1.47	GW	8.8%
OC	17.50	3.77	GP	8.1%
EC	41.33	8.43	GP	9.8%
GU	19.12	0.41	GP	6.9%
CW	28.33	0.64	GP	10.6%

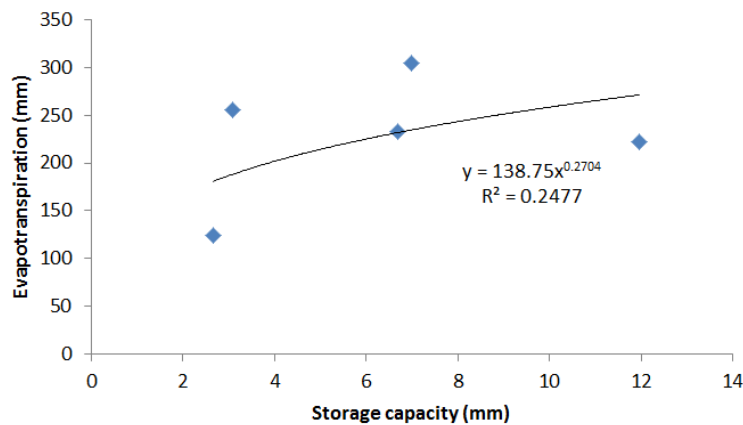*Table 3.21 Sieve and OM content analyses results*

Figure 3.22 Regression analysis between evapotranspiration and storage capacity show that ET may be predicted by storage capacity following first order growth.

Dependent variable	Relationship	r^2	p-value
Uniformity coefficient	y= -0.0007x+0.0766	0.0799	0.645
Coefficient of curvature	y= -0.0062x+0.0783	0.4003	0.252
OM Content	y= -1.3229x+0.1769	0.3358	0.306

Table 3.22 Regression analysis results – all variables were regressed against storage capacity in [mm].

4. Discussion

The accurate interpretation of the moisture data relies on precise sensor calibrations. It is clear from Figures 7.6 and 7.7 (*Appendix B: Raw Data Comparison*) that proper calibrations can have a significant impact on VWC outputs. Due to the discrepancies in calibration protocol explained in *Section 2.3 Sensor calibrations*, it is possible that our measured VWCs do not

reflect true field conditions. Therefore, repeated calibration and testing is recommended for future studies. Nevertheless, assuming our calibrations were within reason, our observational study revealed the potential for variation in green roof performance.

Evapotranspiration rates were substantially different amongst the sampled green roofs. Had we included more sensor replicates, we would have been able to test for the statistical significance of this difference, but we were limited by budgetary constrainst. Total ET ranged from 124.3 mm in the OC roof to 304.5 mm in the PC roof, translating to 13.4% and 32.8% of total observed rainfall, respectively. Calculating ET as the difference between rainfall and runoff (called "retention" in other studies), the green roofs show similar performance to another study in downtown Portland, OR. Spolek (2008) found annual stormwater retention for three green roofs between 12-25%. However, these ranges are considerably less than retention values reported in similar studies. Palla *et al.* (2010) reports average annual retention between 40-80% on a green roof in Italy, and Hutchinson *et al.* (2003) reports 69% average annual retention on other green roofs in Portland. While this discrepancy might be a result of poor ET performance from the green roof plants, it is more likely due to the same reasons that caused low observed storage capacities.

The storage capacities of the green roofs ranged from approximately 2.7mm to 12.0mm. The GU roof had the greatest storage capacity as well as the lowest magnitude of VWC, which leads us to believe that it had the highest rates of ET. Substrates should be designed to have a storage capacity as close to the field capacity as possible, as this maximizes the amount of stormwater retention. However, our calculated range of storage capacities in the field is much lower than the range of field capacities observed in the lab. This is because our field study is seasonal and looks exclusively at the months with the most precipitation. If the drier, summer

months were taken into account, average storage capacity would likely increase because the greater amount of dry weather periods between rain events would allow for the substrates to store more water. This is especially true for Portland, which has dramatically different seasons in terms of rainfall, and receives over half of its precipitation in the rainy season used in this study. Indeed, Spolek (2008) found that "discharge reductions varied widely by month due to seasonal differences in the amount of rainfall." That being said, it is important to remember that the storage capacities here represent the theoretical maximum amount of water that these green roofs can store during a given storm event in Portland's rainy season.

Given this caveat, the results from these data are still useful. What they show is that green roofs in Portland may not perform as well as expected during periods of high precipitation. During these time periods, the substrate does not have sufficient time to "dry out" before the next rain event. In fact, it can take a substrate many days to evapotranspire enough moisture content to allow for adequate storage of subsequent rain events (Fassman & Simcock 2008; Schroll *et al.* 2011) This is problematic because it is precisely during Portland's rainy season that the hydrologic performance of green roofs becomes most critical, as the likelihood of CSOs and the 10-year design storm occurring is greatest.

All five green roofs demonstrated further variability in performance through marked differences in the magnitude of observed VWC (Figure 3.11). The EC roof displayed the greatest VWC despite possessing the shallowest substrate depth. It is possible that this is because it is the only roof with "high" amounts of irrigation, or it could be attributable to poor plant performance – i.e. low rates of ET relative to the substrate depth. However, for the scope of this project and for the purpose of data analysis, it was assumed that irrigation is negligible during the time

period under consideration. This nonetheless stresses the importance of accurately documenting all aspects of the hydrologic balance of studied green roofs – including irrigation.

Regression analysis showed that ET may be predicted by storage capacity following first order growth kinetics. This non-linear relationship shows that the relationship between storage capacity and ET is not one-to-one – in other words, more storage capacity does not necessarily indicate higher performance. This suggests that there may be some optimal storage capacity that balances evapotranspiration while mitigating the cost and structural load produced by increasingly deep substrates. Additional green roofs should be measured with added moisture sensors for replication in order to further investigate this relationship.

The measured substrate properties also demonstrated observable relationships to storage capacity. High uniformity coefficients (C_u>6) were calculated for each substrate. Considering the typical design of green roof substrates – approximately 80% LWA and 20% OM – this is to be expected. A high uniformity coefficient indicates the presence of both large particles (LWA, such as pumice) and small particles (OM content, which includes very fine compost). Furthermore, coefficients of curvature were found to be outside of the range – with the exception of PC – for well graded substrates ($1<C_c<3$), indicating poorly graded substrates for four out of the five green roofs. Lastly, the particle size distributions were found to be within the range recommended for extensive and intensive green roofs by the FLL (2008).

Storage capacity was found to be negatively correlated with coefficient of curvature ($r^2 = 0.400$); as the coefficient of curvature increased, storage capacity decreased. Again, this is to be expected since a higher coefficient of curvature indicates a greater gap in the particle size distribution. The greater this gap, the more poorly graded the substrate, which leads to lower storage capacity.

Storage capacity was found to decrease with increasing OM content, which may be related to findings by Hill *et al.* (2016), who found that maximum water holding capacity – which they define as the difference between the wet and dry densities of the substrate – increases with greater OM content. Our results indicate that higher OM content might allow green roofs to hold more water than they are able to effectively transpire, which further emphasizes the need for additional and comprehensive analysis of green roof substrates and their relation to hydrologic performance. It is also possible that conventional substrate analysis techniques that were developed for natural soils are not as effective for the unique composition of green roof substrates.

5. Conclusions

Calibrated moisture data from five different green roofs in Portland, OR were compared during the rainy winter months. Each green roof displayed a range of magnitudes in volumetric water content (VWC) and field capacity (maximum VWC). Differences in the resultant storage capacities and rates of ET show that there is variability in hydrologic performance. This suggests an ongoing opportunity cost to optimal green roof design in terms of hydrologic performance. Additionally, the observed storage capacities during Portland's rainy season were much lower than the average annual amounts of storage reported in other studies. The implications of this are significant, as the results suggest that green roofs in Portland do not perform as well as expected during the months of highest precipitation, the times when stormwater management is most needed.

Regression analyses did not demonstrate statistically significant results – likely due to the small sample size – however, regression coefficients suggest that trends may emerge with a

greater number of samples. Namely, evapotranspiration may be predicted by storage capacity following first order growth, and storage capacity may be linearly related to substrate organic matter content and coefficient of curvature.

This thesis takes a novel approach on examining the hydrologic performance of green roofs – namely, by studying storage capacity strictly during the rainy season, rather than as an average annual value. As researchers, planners, and developers, we must look beyond average annual storage values, as this can be an inaccurate depiction of hydrologic performance by neglecting seasonal differences. Furthermore, these results indicate the need for plants and substrates that will increase rates of evapotranspiration, allowing the green roof to create sufficient storage space for the subsequent rain event.

The data presented in this thesis represent a snapshot of green roof variability in Portland. Research of additional roofs with greater replication of moisture sensors and increased accuracy in calibration is recommended. While the observed rates of ET and storage capacities are lower than the ideal values for optimal performance, they nonetheless provide quantifiable benefits for stormwater control. Furthermore, it is important to remember that green roofs are just one component of a successful, integrated urban stormwater management system. In fact, these results highlight the need to continue the development of such integrated water systems through rigorous testing, research, and planning. In doing so, we can reduce the environmental impact of the urban landscape and strive to make our cities truly sustainable.

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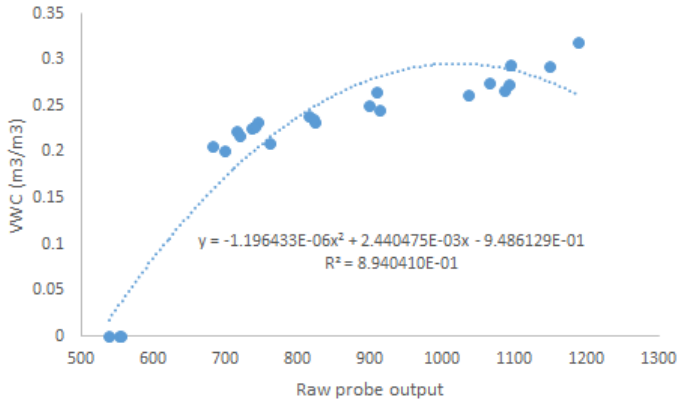
7. Appendix

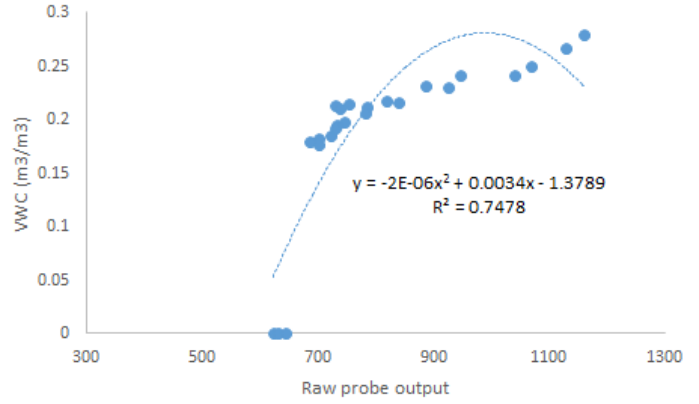## Appendix A: Calibration Curves

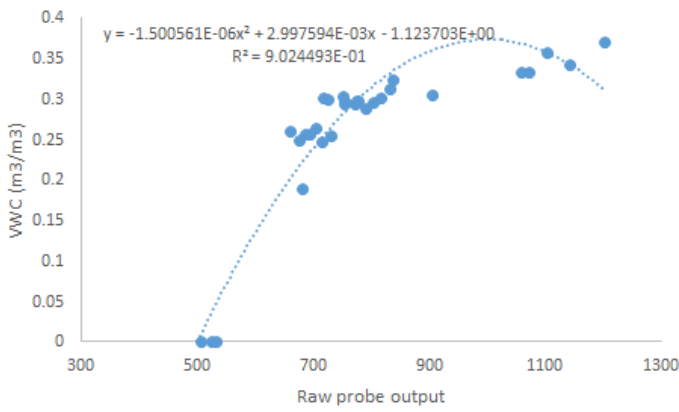
Figure 7.1 PC calibration

Figure 7.2 OC calibration
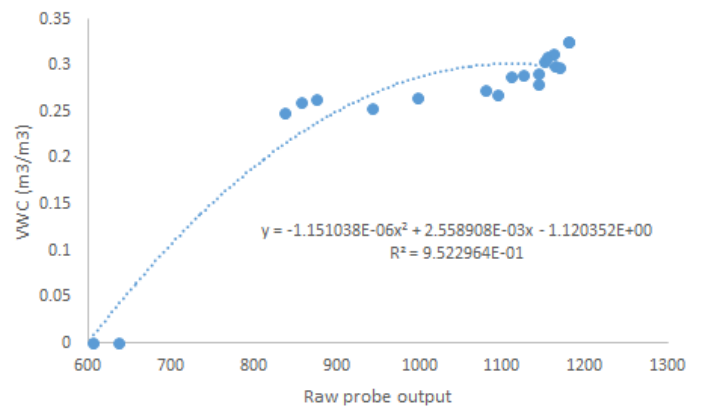

Figure 7.3 EC calibration
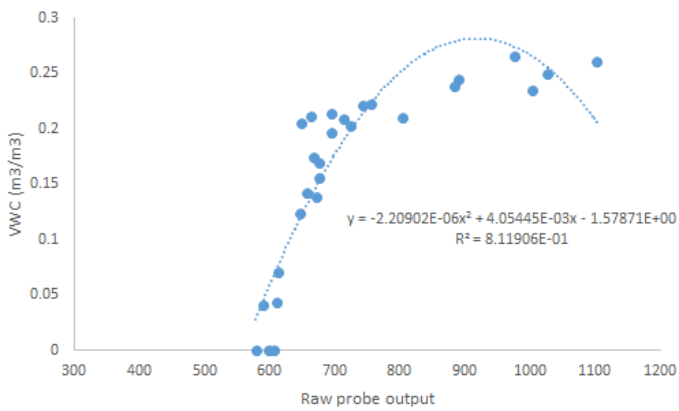

Figure 7.4 GU calibration

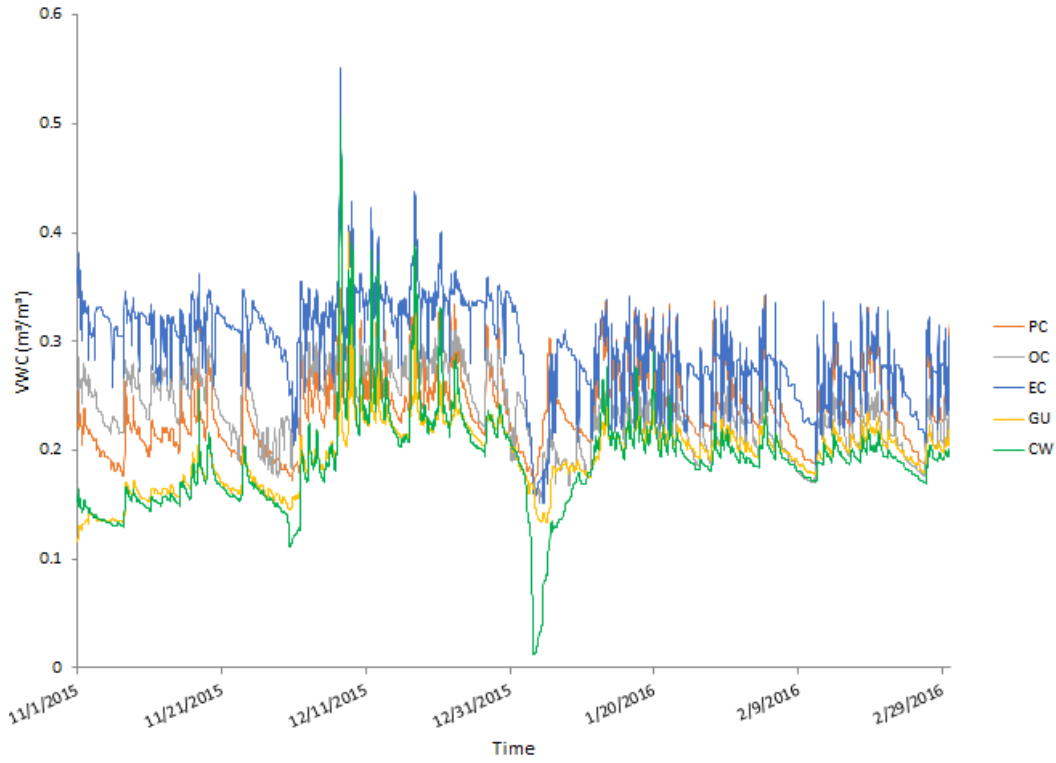*Figure 7.5 CW calibration*

Appendix B: Raw Data Comparison

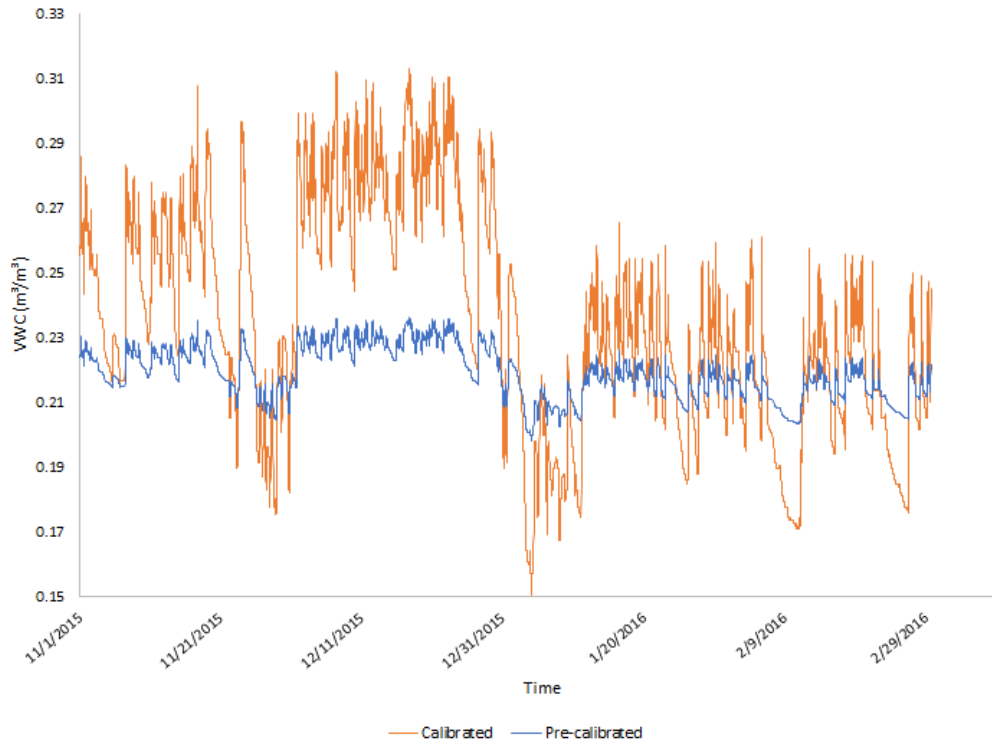*Figure 7.6 Pre-calibrated moisture data for all five green roofs.*

Figure 7.7 Sample comparison between raw data (pre-calibrated) and calibrated data, for OC

Appendix C: Precipitation Data

Date	Raw Tipping Value	Daily Precipitation (mm)	Date	Raw Tipping Value	Daily Precipitation (mm)	Date	Raw Tipping Value	Daily Precipitation (mm)	Date	Raw Tipping Value	Daily Precipitation (mm)
1-Nov-15	48	12.192	1-Dec-15	71	18.034	1-Jan-16	0	0	1-Feb-16	4	1.016
2-Nov-15	4	1.016	2-Dec-15	43	10.922	2-Jan-16	0	0	2-Feb-16	0	0
3-Nov-15	1	0.254	3-Dec-15	52	13.208	3-Jan-16	1	0.254	3-Feb-16	25	6.35
4-Nov-15	0	0	4-Dec-15	37	9.398	4-Jan-16	50	12.7	4-Feb-16	82	20.828
5-Nov-15	1	0.254	5-Dec-15	48	12.192	5-Jan-16	20	5.08	5-Feb-16	28	7.112
6-Nov-15	0	0	6-Dec-15	77	19.558	6-Jan-16	1	0.254	6-Feb-16	0	0
7-Nov-15	67	17.018	7-Dec-15	274	69.596	7-Jan-16	0	0	7-Feb-16	0	0
8-Nov-15	25	6.35	8-Dec-15	158	40.132	8-Jan-16	0	0	8-Feb-16	0	0
9-Nov-15	3	0.762	9-Dec-15	34	8.636	9-Jan-16	1	0.254	9-Feb-16	0	0
10-Nov-15	1	0.254	10-Dec-15	70	17.78	10-Jan-16	0	0	10-Feb-16	0	0
11-Nov-15	16	4.064	11-Dec-15	106	26.924	11-Jan-16	26	6.604	11-Feb-16	16	4.064
12-Nov-15	10	2.54	12-Dec-15	82	20.828	12-Jan-16	99	25.146	12-Feb-16	32	8.128
13-Nov-15	10	2.54	13-Dec-15	39	9.906	13-Jan-16	74	18.796	13-Feb-16	39	9.906
14-Nov-15	0	0	14-Dec-15	3	0.762	14-Jan-16	40	10.16	14-Feb-16	23	5.842
15-Nov-15	37	9.398	15-Dec-15	3	0.762	15-Jan-16	15	3.81	15-Feb-16	0	0
16-Nov-15	60	15.24	16-Dec-15	16	4.064	16-Jan-16	58	14.732	16-Feb-16	18	4.572
17-Nov-15	93	23.622	17-Dec-15	234	59.436	17-Jan-16	91	23.114	17-Feb-16	42	10.668
18-Nov-15	33	8.382	18-Dec-15	32	8.128	18-Jan-16	27	6.858	18-Feb-16	49	12.446
19-Nov-15	63	16.002	19-Dec-15	14	3.556	19-Jan-16	82	20.828	19-Feb-16	51	12.954
20-Nov-15	1	0.254	20-Dec-15	56	14.224	20-Jan-16	10	2.54	20-Feb-16	6	1.524
21-Nov-15	0	0	21-Dec-15	96	24.384	21-Jan-16	30	7.62	21-Feb-16	10	2.54
22-Nov-15	0	0	22-Dec-15	29	7.366	22-Jan-16	36	9.144	22-Feb-16	3	0.762
23-Nov-15	41	10.414	23-Dec-15	78	19.812	23-Jan-16	23	5.842	23-Feb-16	0	0
24-Nov-15	33	8.382	24-Dec-15	5	1.27	24-Jan-16	0	0	24-Feb-16	0	0
25-Nov-15	0	0	25-Dec-15	2	0.508	25-Jan-16	1	0.254	25-Feb-16	0	0
26-Nov-15	0	0	26-Dec-15	0	0	26-Jan-16	8	2.032	26-Feb-16	42	10.668
27-Nov-15	0	0	27-Dec-15	33	8.382	27-Jan-16	5	1.27	27-Feb-16	20	5.08
28-Nov-15	0	0	28-Dec-15	7	1.778	28-Jan-16	56	14.224	28-Feb-16	16	4.064
29-Nov-15	0	0	29-Dec-15	34	8.636	29-Jan-16	47	11.938	29-Feb-16	36	9.144
30-Nov-15	2	0.508	30-Dec-15	0	0	30-Jan-16	22	5.588			
			31-Dec-15	1	0.254	31-Jan-16	8	2.032	**Total for Nov-Feb**		928.624

Table 7.1 Rainfall data obtained from the Portland Fire Bureau rain gauge using the HYDRA Rainfall Network (USGS 2016).