IMPROVING SUSTAINABILITY OF URBAN STREETS VIA RAIN GARDENS – HOW EFFECTIVE ARE THESE PRACTICES IN THE PACIFIC NORTHWEST?

FINAL PROJECT REPORT

by

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16. Abstract

The main goal of this project is to collaborate with the Benton County, City of Corvallis, and multiple other partners to construct, instrument, monitor, model, and evaluate the effectiveness of various engineered green infrastructure practices for improving storm water management on roadways. The project encompasses three integrated tasks related to monitoring, modeling, and cyberinfrastructure. As a result of this project, a research facility (OSU-Benton County Green Stormwater Infrastructure Research Facility, an Oregon BEST Lab or OGSIR) has been developed for conducting field-scale research and testing on green technologies for treatment of roadway stormwater. The major goals of this research project were to:

1) Install a variety of in-situ sensors, spanning from pressure transducers, rain gages, soil temperature and moisture sensors, tensiometers, and infiltrometers, triangular weirs, etc., at rain garden and bioswale sites, and conduct control experiments.

2) Develop and calibrate models for the sites and then test them to predict water balance during observed precipitation conditions.

3) Develop a web-based monitoring portal that will be made available to the community for monitoring these rain gardens in real-time and measure their performance via an embedded modeling framework.

We collaborated with Benton County, Oregon Water Resources Department, and Oregon BEST (http://oregonbest.org/) to develop a three-celled stormwater research facility. Funds from PACTRANS were used in developing a rain garden monitoring system by fabricating multiple instruments and components together. During the summer we constructed the site, and had an inaugural event on Oct 16th 2014 that was attended by a large number of community stakeholders. Some of the monitored environmental parameters include stormwater inflow, pump usage, stormwater outflow, precipitation, wind speed, wind direction, solar radiation, relative humidity, barometric pressure, atmospheric temperature, soil water pressure, soil moisture content, and soil temperature. Instrument calibration and estimates of water balance and system performance was done towards the end of the project. A website (http://research.engr.oregonstate.edu/hydroinformatics/Avery) has been built that will enable near real-time monitoring of system

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List of Abbreviations (optional)

PacTrans: Pacific Northwest Transportation Consortium

WSDOT: Washington State Department of Transportation

OGSIR: OSU-Benton County Green Stormwater Infrastructure Research Facility, an Oregon

BEST Lab

Acknowledgments (optional)

We would, first, like to thank all the graduate and undergraduate students in Civil and Construction Engineering and Water Resources Engineering programs at Oregon State University, specifically Mr. Grant Livingston and Mr. Chris Conatser, who have been critical to the conception and completion of the various project and research steps.

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Executive Summary

The main goal of this project is to collaborate with multiple partners to construct, instrument, monitor, model, and evaluate the effectiveness of various engineered green infrastructure practices for improving storm water management on roadways. The project encompasses three integrated tasks related to monitoring, modeling, and cyberinfrastructure. As a result of this project, a research facility (OSU-Benton County Green Stormwater Infrastructure Research Facility, an Oregon BEST Lab or OGSIR) has been developed for conducting field-scale research and testing on green technologies for treatment of roadway stormwater. The specific objectives of this research project were to:

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[2] Develop and calibrate models for the sites and then test them to predict water balance during observed precipitation conditions.

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We collaborated with Benton County, Oregon Water Resources Department, and Oregon BEST (http://oregonbest.org/) to develop a three-celled stormwater research facility. Funds from PACTRANS were used in developing a rain garden monitoring system by fabricating multiple instruments and components together. During the summer we constructed the site, and had an inaugural event on Oct 16th 2014 that was attended by a large number of community

stakeholders. Some of the monitored environmental parameters include stormwater inflow, pump usage, stormwater outflow, precipitation, wind speed, wind direction, solar radiation, relative humidity, barometric pressure, atmospheric temperature, soil water pressure, soil moisture content, and soil temperature. Instrument calibration and estimates of water balance and system performance was done towards the end of the project. A website (http://research.engr.oregonstate.edu/hydroinformatics/Avery has been built that will enable near real-time monitoring of system performance.

The major contribution of the project is that a new testing facility was constructed and equipped for assessing the effectiveness, in terms of water quality improvement and peak flow reduction, of green infrastructure practices for improving storm water management on roadways. This facility is already being used and there are ongoing conversations with regional stakeholders for its long-term use.

Green infrastructure occurs at all scales, and can be a centerpiece of smart regional and metropolitan planning, ensuring communities have a livable environment, with clean air and water, for generations to come. Recently, smart communities are using green infrastructure for transportation systems (green streets), and green roofs, which can bring the benefits of nature to the built environment. Researchers are amassing a body of evidence to prove that green infrastructure works: these systems are shown to be more cost-effective than outmoded models of grey infrastructure, and also provide far more benefits for both people and the environment. Nature can be incorporated everywhere to provide many benefits at once. The newly developed laboratory will be used to test new technologies that can make green infrastructure systems even more cost-effective.

Chapter 1 Introduction

1.1 Background

Urbanized landscapes increase hydrologic peak flowrates and decrease hydrologic peak delays resulting in flashier hydrographs compared to pre-development hydrologic regimes (Leopold 1975); (EPA 1993). The reason is that conventional stormwater infrastructure, such as gutters, ditches, and pipes, along with impervious surfaces, such as roofs, parking lots, and roads, increases the rate of stormwater conveyance. By concentrating a catchment area's runoff into a relatively small impermeable drainage system, compared to the pre-development landscape, increases the potential for flooding downstream by, for example, causing a 10-year storm to produce the runoff equivalent of a 25-year storm (Meierdiercks 2010; Fletcher et al. 2013; Hollis 1975). Wastewater treatment facilities are frequently overwhelmed by the excessive volumes of stormwater and use combined sewer overflows as a method to manage the urban influent. These combined sewer overflows spill raw sewage into urban waterways. Furthermore, urban stormwater runoff causes an overall degradation of urban stream ecosystems in a condition known as "urban stream syndrome" (Walsh et al. 2005) due to both hydrologic impacts as well as water quality impacts.

Low impact development, (LID), also known as green stormwater infrastructure (GSI) in the Pacific Northwest, was first introduced the early 1990s in Prince George's County, Maryland (Roy-Poirier et al. 2010). These LID methods aim to control the stormwater runoff from a developed site so that the hydrology and water quality approximate that of the pre-development site hydrologic conditions (Davis 2008). LID has gained considerable interest in recent years for addressing the water quantity and water quality issues associated with urban runoff (EPA 2013). For example, many small and large urban communities in the U.S. have undertaken efforts towards transforming their existing street systems into sustainable streets. Sustainable streets, as defined by an Interagency Partnership for Sustainable Communities in June 2009, are multifunctional streets that incorporate multiple ecological, community, and mobility functions. Existing sustainable streets projects across the country have primarily vested in introducing features such as natural drainage practices for improved storm water management, and increased multimodal access.

One of the most well studied forms of GSI is bioretention that has the potential to address the issues associated with conventional stormwater infrastructure next to roadways. Bioretention has been defined as "a landscaped depression that receives runoff from up gradient impervious surfaces, and consists of several layers of filter media, vegetation, an overflow weir, and an optional underdrain," (Liu et al. 2014). Bioretention is used to reduce the effects of hydromodification (Poresky and Palhegyi 2008), stormwater pollution (EPA 1999), and combined sewer overflows (Clayden and Dunnett 2007); (Cramer 2012). Some examples of bioretention include rain gardens, bioswales, and stormwater planters.

While implementation of natural drainage systems (e.g., planting strips, rain gardens, bio-swales, filter strips, etc. built into the sidewalks) are known to improve environmental sustainability of streets because of their ability to treat roadway runoff, filter out roadway pollutants, and prevent sewer overflows after heavy storm events, there is lack of data and understanding on seasonal effectiveness of these practices in capturing and treating runoff from different street hierarchies (e.g., primary or arterial streets, secondary or collector streets, tertiary or local streets, etc.). This lack of knowledge poses a limitation to small and large urban cities, especially those in the Pacific Northwest (e.g., Portland and Corvallis in Oregon, and Seattle and

Olympia in Washington, etc.), that have a unique wet-and-dry climate pattern. Effectiveness or ineffectiveness of these practices poses questions on the costs and benefits tradeoff, since many Pacific Northwest cities are currently investing significant funds towards incorporating such practices in their transportation infrastructure.

The main goal of this project is to collaborate with the Benton County, City of Corvallis, and multiple other partners to construct, instrument, monitor, model, and evaluate the effectiveness of various engineered green infrastructure practices for improving storm water management on roadways. The project directly addresses the PacTrans theme on "Safe and Sustainable solutions for the diverse transportation needs of the Pacific Northwest" by investigating the effectiveness of these runoff treatment systems in a local Oregon community that is working on improving the environmental sustainability of its street systems. It also accomplishes Secretary of Transportation's strategic goals on Environmental Sustainability and Livable Communities by collaborating with the City of Corvallis' in establishing roadways that can capture and treat storm runoff, offer alternative transportation routes, increase urban green space, and improve the health of the community.

1.2. Specific Objectives

Specific objectives of this research project were to:

Objective 1: Install a variety of in-situ sensors, spanning from pressure transducers, rain gages, soil temperature and moisture sensors, tensiometers, and infiltrometers, triangular weirs, etc., at rain garden and bioswale sites, and conduct control experiments.

Objective 2: Develop and calibrate models for the sites and then test them to predict water balance during observed precipitation conditions.

Objective 3: Develop a web-based monitoring portal that will be made available to the community for monitoring these rain gardens in real-time and measure their performance via an embedded modeling framework.

Chapter 2 Literature Review

Field studies have shown that bioretention practices reduce impervious surface hydrologic impacts by reducing peak magnitudes and delaying the time to the peak (Table 1). The hydrologic performance can be described with the metrics of peak ratio and peak delay. The peak ratio is the ratio of peak outflow to peak inflow, and the peak delay is the elapsed time between inflow and outflow peaks. A complete description of these metrics can be found in the methods. The variables that can affect hydrologic performance include regional hydrology, drainage configuration, and surface storage volume (Brown et al. 2013). Additional variables include media depth (Brown and Hunt 2010), media composition (Carpenter and Hallam 2009); (Hsieh and Davis 2005); (Paus et al. 2014), antecedent moisture conditions (Davis 2008); (Muthanna et al. 2008), plant selection; (Le Coustumer et al. 2012) ; (Barrett et al. 2012) , and season (Hunt et al. 2008); (Emerson and Traver 2008).

The range of values reported for peak ratio and peak delay in **Table 2.1**, along with the variables stated above, complicate the process of accurately upscaling bioretention models from the site scale to watershed scale. Additionally, at the design stage, engineers and landscape architects need to be able to accurately estimate bioretention hydrologic performance for proper sizing. Furthermore, unlike conventional stormwater infrastructure, bioretention systems grow and change over time because they are living. This difficult in predictability of hydrologic function presents an issue for cities implementing bioretention to meet specific objectives for urban stormwater management.

Table 2.1 Review of bioretention peak hydrology literature. n Storms = # storms analyzed, A_{BR} = bioretention area. A_{CT} = catchment area, R_{peak} = peak ratio. P_{delay} = peak delay, reported as typical or mean value. *lag time was reported instead of peak delay. **Average of 180 min for medium rain, and 80 min for heavy rain.

Author	Year	Location	n Storms	A_{CT}	A_{BR}	A_{BR}/A_{CT}	R_{Peak}			P_{delay}
				m^2	m^2		Median	Mean	Std. Dev.	minutes
Davis	2008	Maryland	49	1260	28	2.2%	0.51	0.48		120
		Maryland	49	1260	28	2.2%	0.42	0.40		
Dietz and Clausen	2005	Connecticut	1	107	9	8.6%		0.35		60
Hatt et al.	2009	Melborne, Australia	17	4500	15	0.3%	0.18	0.21	0.13	
		Melborne, Australia	4	1000	20	2.0%	0.15	0.16	0.03	
Hunt et al.	2008	North Carolina	16	3700	229	6.2%	0.01	0.01	0.01	180
Li et al	2009	Maryland	22	2600	181	7.0%	0.14			
		Maryland	60	4500	102	2.3%	0.02			
		North Carolina	46	5000	317	6.3%	0.01			
		North Carolina	46	4800	317	6.6%	0.01			
		North Carolina	31	3600	162	4.5%	0.04			
		North Carolina	33	2200	99	4.5%	0.1			
Muthanna et al.	2008	Norway	44	20	1	4.8%	0.65	0.56	0.29	90*
Olszewski and Davis	2013	Maryland	197	3700	102	2.8%		0.83		
Passeport	2009	North Carolina	16	3450	102	3.0%		0.82		
		North Carolina	13	3450	102	3.0%		0.86		
Schlea et al.	2014	Ohio	4	2894	27	0.9%	0.46	0.42	0.32	16
		Ohio	3	869	19	2.1%	0.29	0.31	0.28	
UNHSC	2012	New Hampshire				12.5%		0.25		266*
		New Hampshire				0.6%		0.21		309*
		New Hampshire				0.6%		0.16		216*
		New Hampshire				3.1%		0.5		61*
Yang et al.	2013	Ohio State University	8	63	14	22.1%		0.17		130**

One of the variables that affects bioretention hydrology that has not been well studied is bioretention establishment, which is defined here as the indefinite period of time following bioretention construction activities and planting during until the system shows stability in hydrologic performance. Previous work in bioretention establishment has investigated soil permeability. A trend of decreased permeability followed by increased permeability has been attributed to surface clogging and soil media compaction followed by macropore and preferential flow path development (Hatt et al. 2009), see **Figure 2.1**.

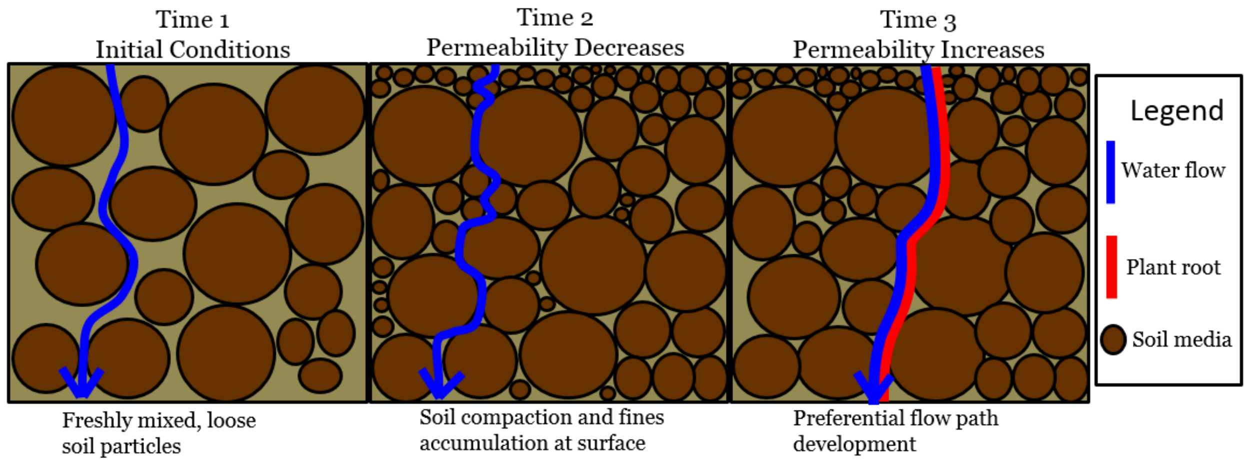

Figure 2.1 Conceptual diagram of bioretention establishment.

Both vegetation (Le Coustumer et al. 2012) and earthworms through bio-perturbation (Greene et al. 2009) have been shown to maintain or increase soil permeability over time. However, the effect of bioretention establishment on peak flow hydrology has not been well researched. Filling this knowledge gap is important to improve bioretention design, as there is still a lack of a model that can be used at the design stage to accurately predict hydrologic performance (Liu et al. 2014). Furthermore, a greater understanding of the bioretention establishment could help designers to properly size bioretention systems to meet stormwater management criteria.

Chapter 3 Study Site/Data

3.1 Site Description

The *OSU-Benton County Green Stormwater Infrastructure Research Facility, and Oregon Best Lab* is a three cell bioretention facility, installed in the summer of 2014, which captures runoff from the Benton County Public Works transportation yard. This 9,300 m^2 catchment area is used to store equipment and materials for road construction, and it consists of large trucks and tractors, road fill and base material, raw asphalt, paint, a refueling station, and a staff parking lot. LiDAR point cloud data of the site was used to estimate the catchment boundary, and it was confirmed with field evaluation during a runoff producing storm event. About 59% of the catchment area is asphalt or has a roof, and the other 41% is clay with gravel on top that has been highly compacted from all of the heavy equipment. The average annual precipitation is 1,100 mm with most of the precipitation falling during the fall, winter, and spring. According to a local Willamette River historian, the area surrounding the catchment was likely Willamette Valley wetland prairie and prairie habitat prior to Euro-American settlement (Benner 2015), which guided the plant selection for the facility. Before project implementation, the runoff from the catchment area flowed into the City of Corvallis' piped stormwater network and into the local Mill Race Creek. This creek currently is managed to drain stormwater from southern Corvallis into the Marys River. However it has been verified by the Oregon Department of Fish and Wildlife in preliminary survey work to host spring Chinook salmon, a federally listed endangered species (Hans 2015), which may change management objectives.

3.2 Design and Construction

The design of the bioretention cells was guided by the Oregon State University Stormwater Extension rain garden sizing spreadsheets and drawing design details (Extension

2014), the LID Center bioinfiltration sizing spreadsheets (Low Impact Center Development 2015), and the Oregon Rain Garden Guide (Emanuel et al. 2009). Runoff from the catchment area is intercepted by an inline 6,700 L concrete underground storage tank, and pumped at approximately 2.2 L/s by a Liberty 251 automatic pump into a 5,500 L concrete sedimentation bay. Water then flowed by gravity through the weirs and into the bioretention cells for treatment before being captured by an underdrain and returned to the existing stormwater pipe network. See **Error! Reference source not found.** for a schematic of the facility.

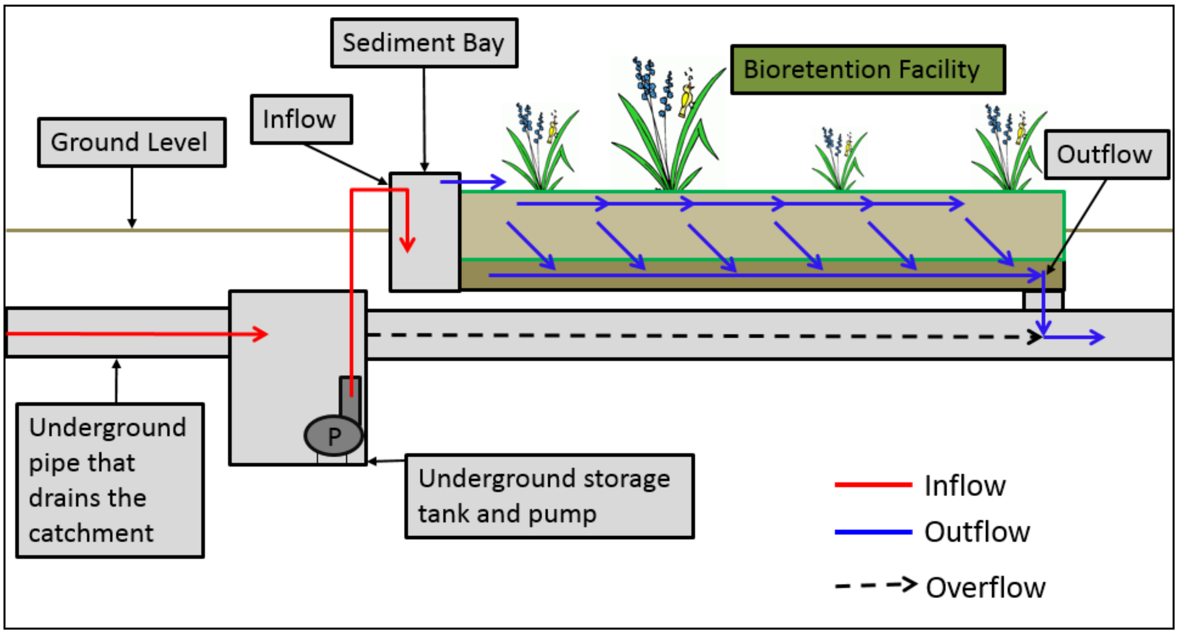

Figure 3.1 Schematic of the bioretention facility.

Three 90° V-notch weirs were installed at the same level in the sediment bay to allow for equal stormwater flow into each of the 3.2 m wide by 28.5 m long parallel bioretention cells. The weirs were sized by modeling the pump and dividing its flow into three for the three weirs and by using a standard weir equation to model the flow of water through the weirs. Vertical walls made from steel H-piles and repurposed lumber separated the cells, and a 1.1 mm (45 mil) EPDM fish safe pond liner was installed around the walls and in the cells to prevent flow interference between cells and with the groundwater table. See Error! Reference source not found..**2** for a typical cross section and Error! Reference source not found. for a plan view of the site.

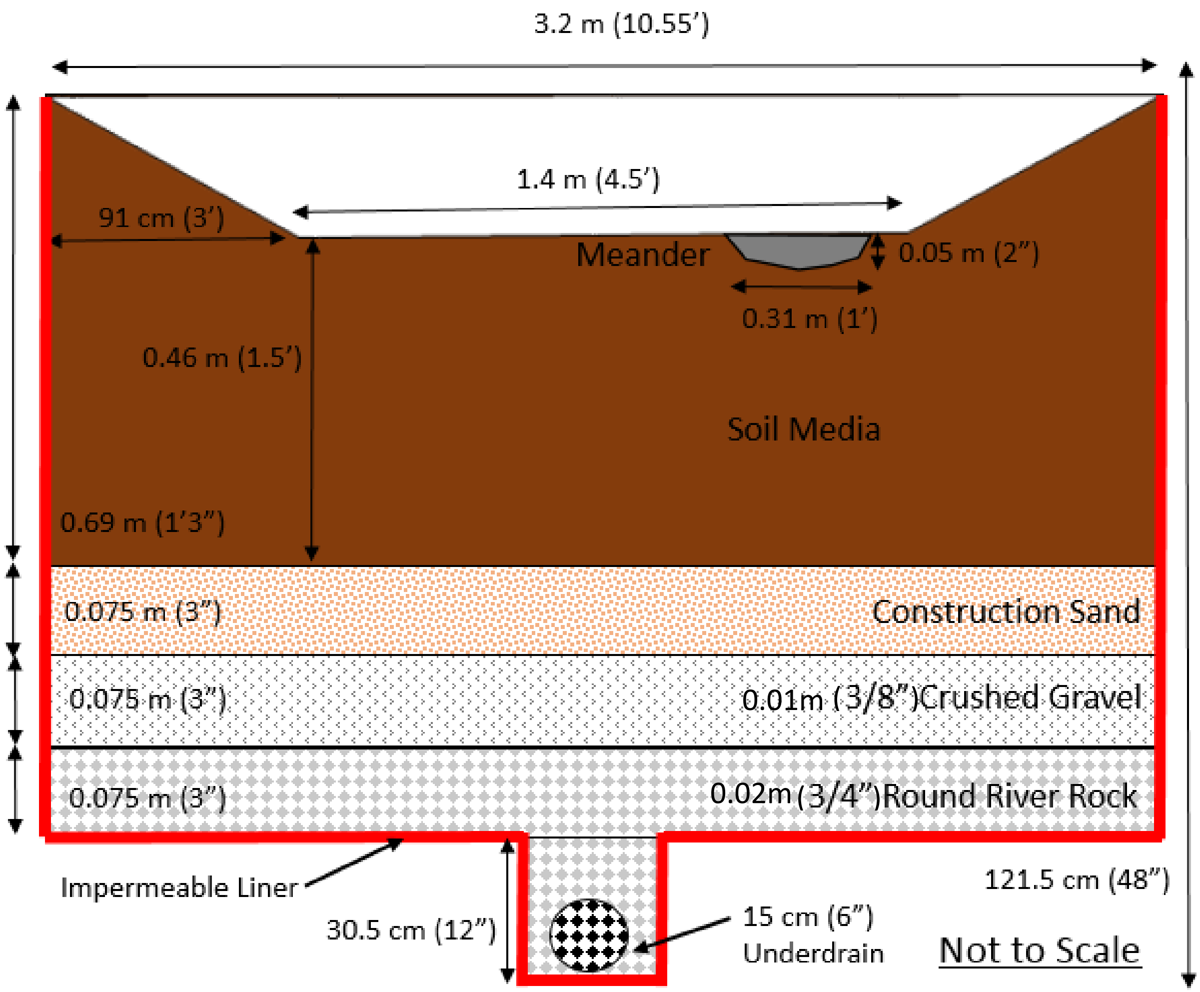

Figure 3.2 Typical bioretention cross section with meander, soil media, construction sand, crushed gravel, round river rock, underdrain, and impermeable liner.

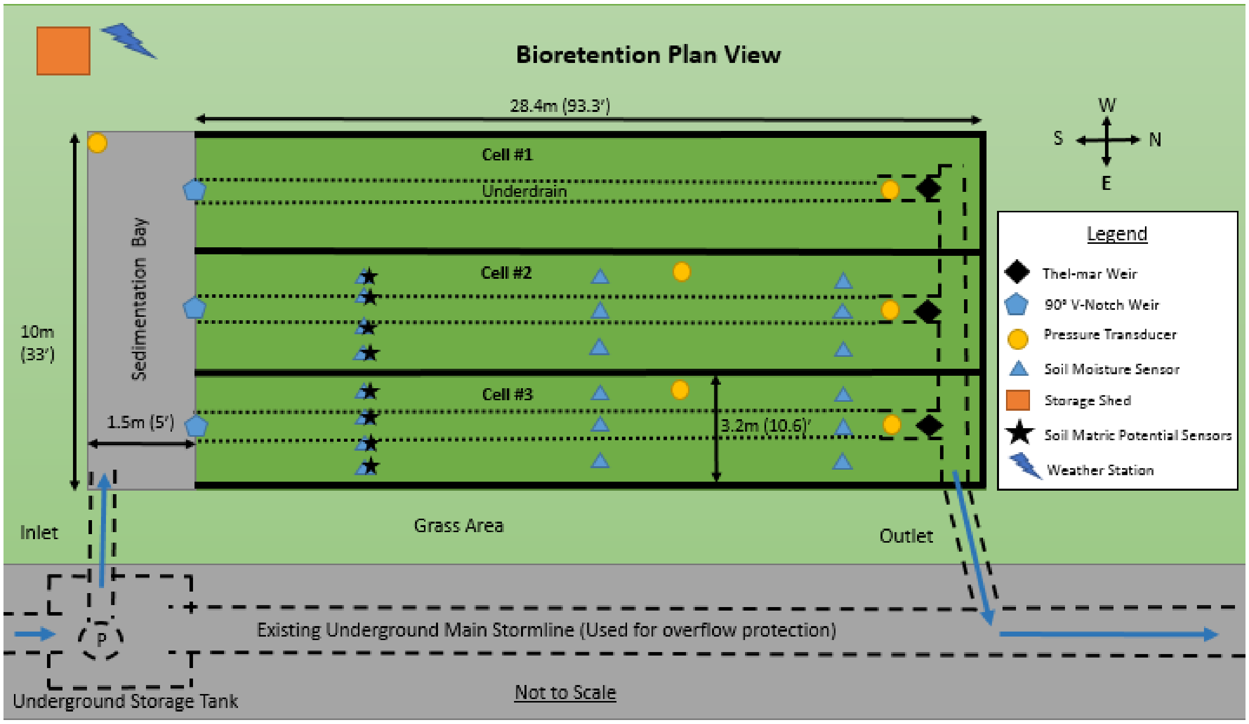

Figure 3.2 Bioretention facility plan view. Note that dotted and dashed lines are perforated and solid pipes, respectively, below ground level.

A 152 mm (6 in.) thin wall perforated underdrain pipe was placed at the bottom of each cell above the impermeable liner and covered with a non-woven 170g (6 oz) geotextile to prevent clogging. The storage/filtration layers in the facility consist of 1.9 cm (3/4 in.) rounded river rock, 0.95 cm (3/8 in.) crushed gravel, and construction sand. The soil media consisted of a 2:1:1 mixture of the site's native silty clay loam, municipal yard waste compost (as a source of nutrients for the plants), and mint compost (as a source of organic matter). The swale side slopes were 4:1. A 1.9cm (3/4 in.) rounded river rock meander underlain by landscape fabric was installed in the center of the swales for aesthetics and increased flow conveyance. A drip irrigation system was installed to keep the plants alive during the dry summers which are typical for the Willamette Valley. Cell 1 was left as bare soil, Cell 2 was planted with native grasses, and Cell 3 was planted with mixed vegetation. The dataset from Cell 3 was the most complete, therefore it was used in the following analysis. The Cell 1 dataset lacked fall and spring data, and the Cell 2 dataset lacked winter data. Planting activities primarily took place in mid-September, however, additional seeds and bulbs were added throughout the fall, and several native plants came in on their own, possibly from the native soil's seed bank. See Appendix A for a full list of plant species used in Cell 3. The bioretention cells were maintained with manual hand weeding in the beginning of spring.

Chapter 4 Method

4.1 Instrumentation and Monitoring

The influent water level height used for flow rate calculations was monitored with a pressure transducer anchored onto the concrete wall of the sediment bay. Initially, a Steven's SDX 1.5m (5 ft) range pressure transducer was installed, however, it failed on January 23, 2015, and water level data was not collected again until a temporary replacement Decagon CTD-10 was installed on February 26, 2015. A more accurate 0.76m (2.5ft) range SDX pressure transducer replaced the Decagon CTD-10 on April 9, 2015 until the end of the monitoring period on May 15th, 2015.

The underdrain effluent was monitored with a SDX 1.5m (5 ft) range pressure transducers installed in a stilling well upstream of a 15.2cm (6 in.) Thel-Mar compound weir. Overflows were not monitored, but were assumed to be negligible due to field observations during heavy storm events. A MetONE Weather Station was used to measure wind speed, wind direction, relative humidity, air temperature, and barometric pressure. An Apogee SP-212 pyranometer was used to measure solar radiation, and a MetONE tipping bucket rain gauge was used to monitor precipitation. Soil moisture and temperature was measured with 10 Steven's Hydraprobe II sensors, and soil matric potential was measured with TensioMark Tensiometers. All of the data was logged at 15 minutes intervals with a Campbell Scientific CR 1000 Data Logger powered by a 100W solar panel and 12V lead-acid deep cycle battery. The relative placement of the instrumentation can be viewed in Error! Reference source not found. in the previous chapter. Each instrument was placed to be representative of the area it surrounds.

4.2 Pressure Transducer Bias Correction

The datum for the inlet and outlet pressure transducers drifted over time, which is common for fine scale water level sensors (Sorensen and Butcher 2011). The correction of this drift was made possible due to the physical setup of the weirs. After a storm event, the water level would drain to the bottom of the weirs and stabilize until the next storm event or evapotranspiration occurred. The data was adjusted by locating intervals of time where the data showed that the water level was stable at the bottom of the weir following a storm event. The distance between the pressure transducer's zero datum and the bottom of the V-notch weir is referred to as h_{weir} for the remainder of this report. Notice that $h_{measured}$, the pressure transducer's measured water level, is equal to h_{weir} after a storm event. This physical process that lead to the relationship between $h_{measured}$ and h_{weir} was used as the basis for development of the drift correction method. See Error! Reference source not found. for reference.

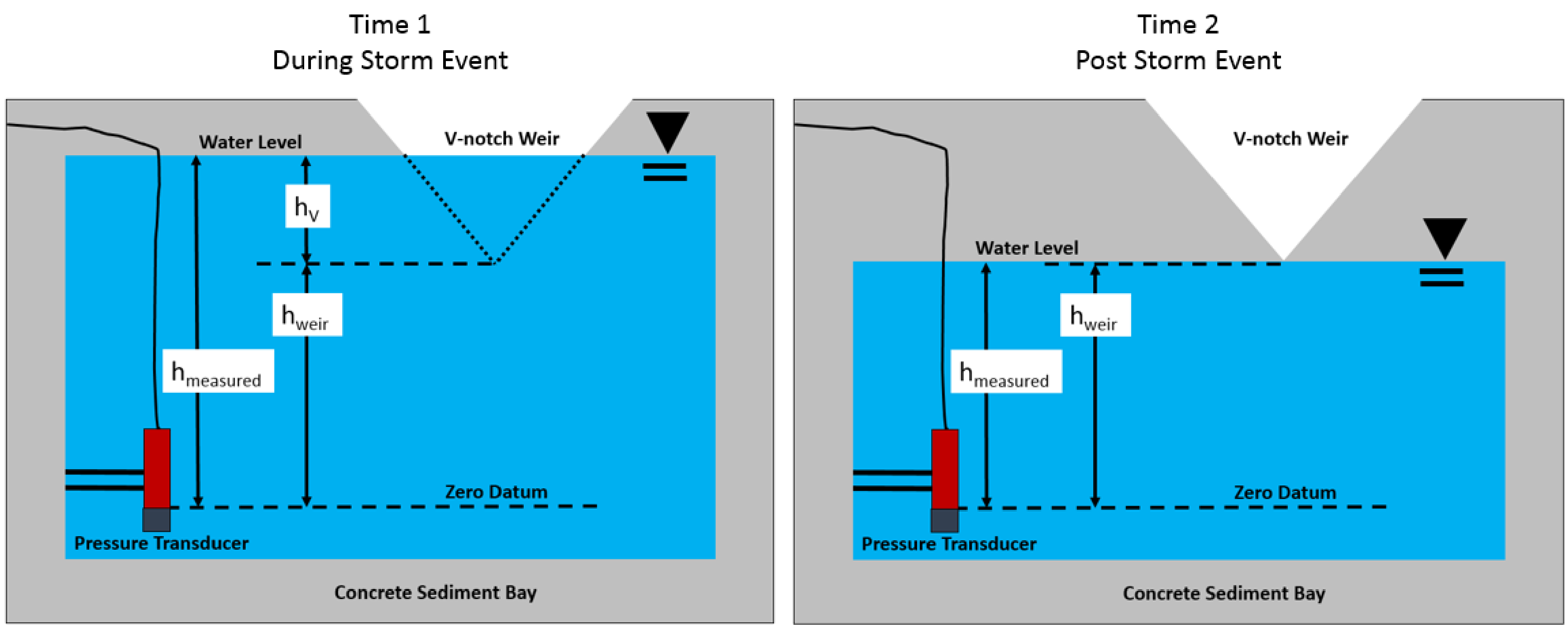

Figure 4.1 The change of water level height from during a storm to after a storm. The relationship between $h_{measured}$ and h_{weir} after a storm event was used as the basis for the drift correction method.

The general procedure for the drift correction was as follows:

1. Find a relative stable interval of $h_{measured}$ equal to h_{weir} following a storm event using graphical analysis and examination of the water level time series numerical data.
2. Find the average value of h_{weir} for the stable interval.
3. Find the applicable range of each h_{weir} in the water level time series dataset, and subtract h_{weir} from $h_{measured}$ to obtain h_V for flowrate calculations (see Volumetric Water Balance below).

The applicable range of h_{weir} was determined through graphical analysis by using a horizontal line placed at the average value of h_{weir} and observing where the line no longer matched with the relatively stable measured water level following a storm event.

4.3 Flowrate Calculations

Flowrates were calculated using the drift corrected values of h_V. An additional 2mm was added to h_V to account for the curvature at the bottom of the V-notch weir, which kept water from draining down to the exact vertex of the V. The inflow rates were calculated with a standard V-notch weir equation (Eqn. 4.1).

$$Q_{in} = \frac{8}{15} C_d (2g)^{\frac{1}{2}} \tan\left(\frac{\theta}{2}\right) h_V{}^{5/2} \tag{4.1}$$

Where g is gravity, and θ is the angle of the v-notch. A standard value of 0.6 was used for the coefficient of discharge, C_d.

The outflow rates were calculated using a rating curve that was based on linear interpolation of the discharge table provided by the weir manufacturer, Thel-Mar. All outflow rate calculations used the drift corrected dataset except for the three storm events discussed below, which used both the drift corrected and water balance calibrated dataset.

4.4 Water Balance Calibration

A novel method using a water balance approach was used to calibrate the $h_{measured}$ value for the underdrain stilling well pressure transducer. The water balance was computed for three 96 hour storm events (fall, winter, spring) using system inputs of cumulative weir inflow, V_{pumped}, and cumulative direct precipitation, $V_{precip,}$ on the facility and system outputs of cumulative underdrain weir outflow $V_{underdrain}$, and cumulative evapotranspiration, V_{ET} (Eqn. 4.2).

$$V_{pumped} + V_{precip} - V_{underdrain} - V_{ET} = \Delta S \qquad (4.2)$$

The change in storage, ΔS, was computed using the average change of the 10 soil moisture sensors in the bioretention cell before and after the storm events, which was multiplied by the volume of the soil media using an average depth of 0.6m. The evapotranspiration, V_{ET}, was calculated using the Hargreaves method with the Samani correction for net.

The total volume, V, of each 96 hour storm event was computed using a trapezoidal numerical integration of the volume flux, Q, with a time step, Δt, of 15 minutes (Eqn. 4.3).

$$V = \int_{t_1}^{t_n} Q\, dt = \sum_{i=1}^{i=n}((Q_{t_i} + Q_{t_{i+1}})/2 * \Delta t) \qquad (4.3)$$

The residual of the water balance was used to calibrate the underdrain stilling well’s value for h_V by minimizing the difference between the residual and the total outflow volume.

4.5 Peak Hydrology Metrics

Bioretention hydrologic performance was quantified with the metrics of peak flow ratio (Davis 2008) and the peak delay time. See Eqns. 4.4-4.5.

$$R_{peak} = \frac{Q_{peak-out}}{Q_{peak-in}} \tag{4.4}$$

Where $Q_{peak\text{-}in}$ (L/s) is the peak inflow rate, and $Q_{peak\text{-}out}$ (L/s) is the corresponding peak outflow rate.

$$P_{delay} = T_{Qpeak-out} - T_{Qpeak-in} \tag{4.5}$$

Where P_{delay} is the difference in the time between the inflow peak and its paired outflow peak.

In general, a lower value of R_{peak} is desirable because it means that the outflow peak is smaller in magnitude than the inflow peak, and a higher value of P_{delay} is desirable because it means that the outflow peak was delayed by greater period of time.

4.6 Drain Tests

The bioretention cell was brought to field saturated conditions in November 2014 and March 2014 by closing the underdrain outlet valves and allowing the cells to pond and reach overflow conditions. Once saturated and ponded, the underdrain outlet valves were opened, and the cells were drained. Water level height for the outflow recession curve was collected and compared for these two drain tests.

4.7 Bioretention Establishment Hydrologic Characterization

The peak flow monitoring period took place during the fall, winter, and spring of 2014-2015. Peak ratio and peak delay statistics were computed for each season and compared to investigate the peak hydrologic response of bioretention establishment.

Chapter 5 Results

5.1 Pressure Transducer Drift Correction

Pressure transducer water level measurement drift was observed throughout the monitoring period. The drift in the sediment bay pressure transducers had a magnitude of 29mm for the 1.5m range Steven's SDX pressure transducer over the course of 93 days, 18 mm for the Decagon CTD pressure transducer (42 days), and 2mm for the Steven's 0.76m pressure transducer (36 days). The underdrain stilling well pressure transducer had a drift of 25mm over the course of the 274 day during the monitoring period.

A total of 21 drift corrections were made for the sediment bay pressure transducers and 22 for the underdrain stilling well pressure transducer. A drift correction was applied on average every 8.1 days with a standard deviation of 8.4 days for the sediment bay pressure transducers, and 7.8 days with a standard deviation of 4.8 days for the underdrain stilling well pressure transducers.

An example of the drift correction can be seen in Error! Reference source not found..

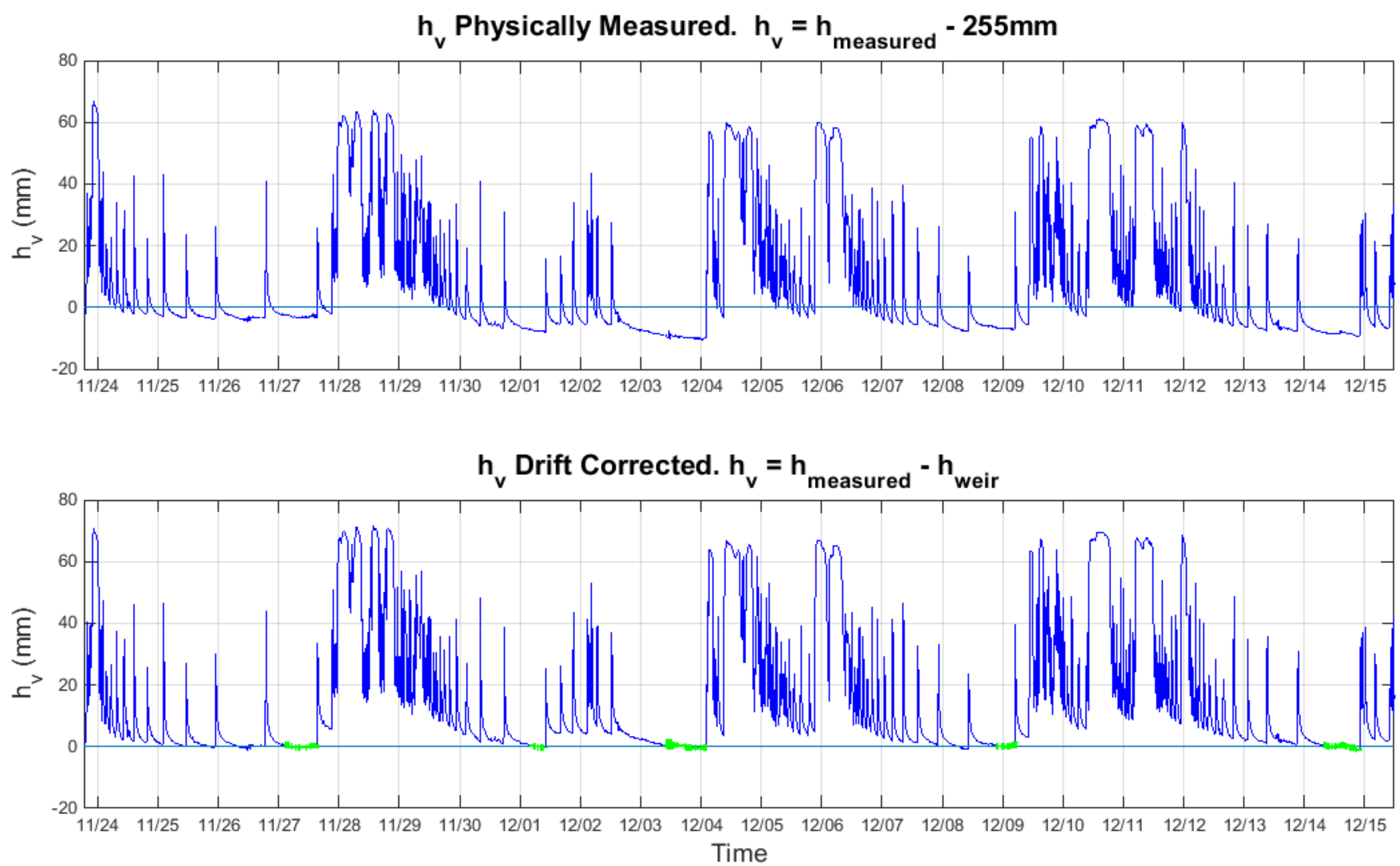

Figure 5.1 The observed sediment bay 1.5m range SDX pressure transducer drift (top) and applied drift correction (bottom). The physically measured distance for h_{weir} (255mm) was subtracted from $h_{measured}$ to obtain h_V (top). The relatively stable h_{weir} intervals, highlighted in green, were applied to their applicable ranges (generally 1 storm) to complete the drift correction. The high frequency of peaks is due to the automatic pump turning on and off in response to precipitation.

5.2 Water Balance

5.2.1 Cumulative Volumes

The drift corrected data were used to calculate inflow and outflow volumes to validate the water balance. Cumulative inflow and outflow volumes were calculated from the flow rates using a trapezoidal method for numerical integration. Direct precipitation on the cell and evapotranspiration from the cell were included in the total inflows and outflows, respectively. The cumulative volumes were compared to visualize the water balance, see Error! Reference source not found..

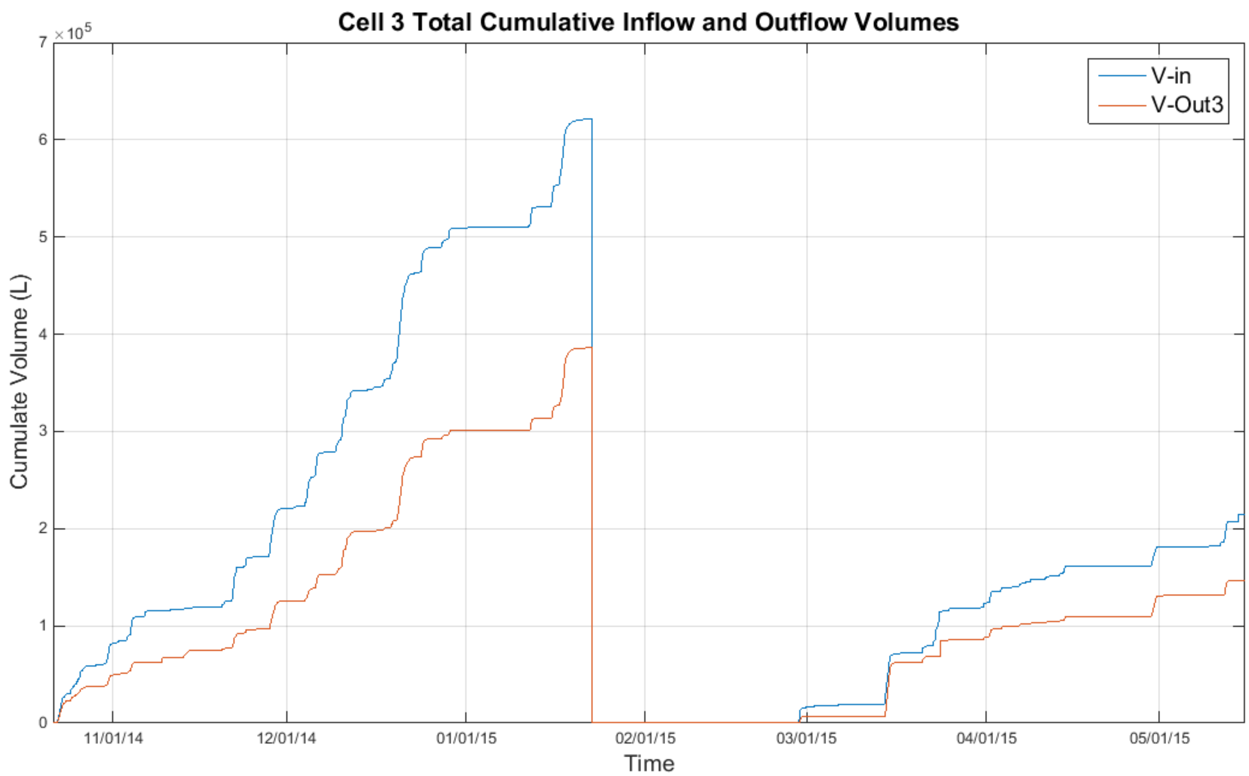

Figure 5.2 The total cumulative inflows were greater than the total cumulative outflows by 370 m^3, and they could not be accounted for by the change in soil water storage alone. The data gap between late January and late February was due to sensor failure.

The shape of the inflow and outflow curves are in sync, but the outflow curve grows more rapidly. The total inflow volume was 900 m^3, the total outflow volume was 530 m^3, and the total estimated pore space was 26 m3 (assuming a soil porosity of 0.5). The difference between the total inflows and outflows could not be accounted for by the change in the soil water storage alone. Therefore, the water balance was not validated.

5.2.2. Fall, Winter, and Spring Storm Water Balance Calibration

Three storm events were selected from the fall, winter, and spring for water balance analysis. The h_{weir} values from the underdrain stilling well pressure transducer were calibrated to "close" the water balance. Estimated evapotranspiration and direct precipitation values were kept constant, as they were 1 to 3 orders of magnitude smaller than the weir flow values and considered negligible. Target values for each outflow h_{weir} calibration were calculated as the residual of the volumetric water balance for each storm event. Residuals were on the same order of magnitude as the total inflow volume before the water balance calibration, and were decreased to less than 1% of the total inflow volume after the water balance calibration. The percent error, calculated as the residuals' percentage of the total inflow volume, decreased from 61%, 66%, and 47% to 0.85%, 0.09%, and 0.17% for the fall, winter, and spring storms respectively (

Table 5.1**)** and (**Table 5.2)**.

Table 5.1 The volume of each element in the water balance was calculated. The $V_{underdrain}$ and residual are highlighted for comparison with Table 3. *The error is reported as the residual's percentage of the total inflow volume.

Pre-Calibration Volume Balance							
Storm	**V_{pumped}**	**V_{precip}**	**$V_{underdrain}$**	**V_{ET}**	**ΔS**	**Residual**	**Error***
Season	**L**	**L**	**L**	**L**	**L**	**L**	**%**
Fall	3.2E+04	2.0E+03	**1.5E+04**	8.3E+01	-1.4E+03	**2.1E+04**	**61%**
Winter	2.2E+04	1.1E+03	**8.3E+03**	3.8E+01	-3.8E+02	**1.5E+04**	**66%**
Spring	1.9E+04	2.5E+03	**1.1E+04**	1.4E+02	3.8E+02	**1.0E+04**	**47%**

Table 5.2 The pumped inflow volume and underdrain outflow volume changed for each storm from the pre-calibration volume balance to the post-calibration volume balance due to the h_{weir} adjustments. *The error is reported as the residual's percentage of the total inflow volume.

Post-Calibration Volume Balance							
Storm	**V_{pumped}**	**V_{precip}**	**$V_{underdrain}$**	**V_{ET}**	**ΔS**	**Residual**	**Error***
Season	**L**	**L**	**L**	**L**	**L**	**L**	**%**
Fall	3.2E+04	2.0E+03	**3.6E+04**	8.3E+01	-1.4E+03	**288**	**0.85%**
Winter	2.2E+04	1.1E+03	**2.4E+04**	3.8E+01	-3.8E+02	**20**	**0.09%**
Spring	1.9E+04	2.5E+03	**2.1E+04**	1.4E+02	3.8E+02	**38**	**0.17%**

The h_{weir} values were adjusted to the nearest 0.1mm to minimize the difference between the underdrain outflow volume and the target volume. The h_{weir} values were decreased by 7.0mm, 7.8mm, and 5.7mm for the fall, winter, and spring, storms respectively, which causes the outflow rates to increase. See **Table 5.3** for an example of the iterations used to calibrate h_{weir}.

Table 5.3 Outflow h_{weir} calibration was accomplished by minimizing the difference between the target (the drift corrected water balance residual) and the estimated underdrain outflow volume, $V_{underdrain}$, through iteration.

Outflow h_{weir} Calibration by Volume Balance									
	Fall Storm			Winter Storm			Spring Storm		
	h_{weir} adjustment	$V_{underdrain}$	Difference	h_{weir} adjustment	$V_{underdrain}$	Difference	h_{weir} adjustment	$V_{underdrain}$	Difference
Trial	mm	L	L	mm	L	Balance	mm	L	Balance
1	5	28,150	7,204	5	16,525	7,115	5	19,554	1,649
2	6	31,784	3,570	7	21,334	2,306	5.5	20,689	515
3	6.9	34,847	507	7.7	23,325	315	5.6	20,926	277
4	7	**35,642**	(288)	7.8	**23,620**	20	5.7	**21,165**	38
5	7.1	36,043	(689)	7.9	23,922	(282)	5.8	21,407	(203)
6	8	39,816	(4,462)	8	24,228	(588)	8	27,284	(6,081)
	Target:	**35,354**	L	Target	**23,640**	L	Target	**21,203**	L

Once the underdrain stilling well h_{weir} values were calibrated to decrease the water balance residuals to below 1% of the total inflow, the h_{weir} values were subtracted from the $h_{measured}$ values to obtain calibrated h_V for flowrate calculations. These flowrates calculations for the fall, winter, and spring storm events were considered both drift-corrected and water balance calibrated. The adjusted weir flowrates were plotted to visually validate the correction. See Error! Reference source not found. and Error! Reference source not found. for the inflow and outflow rates of the pre and post water balance calibration.

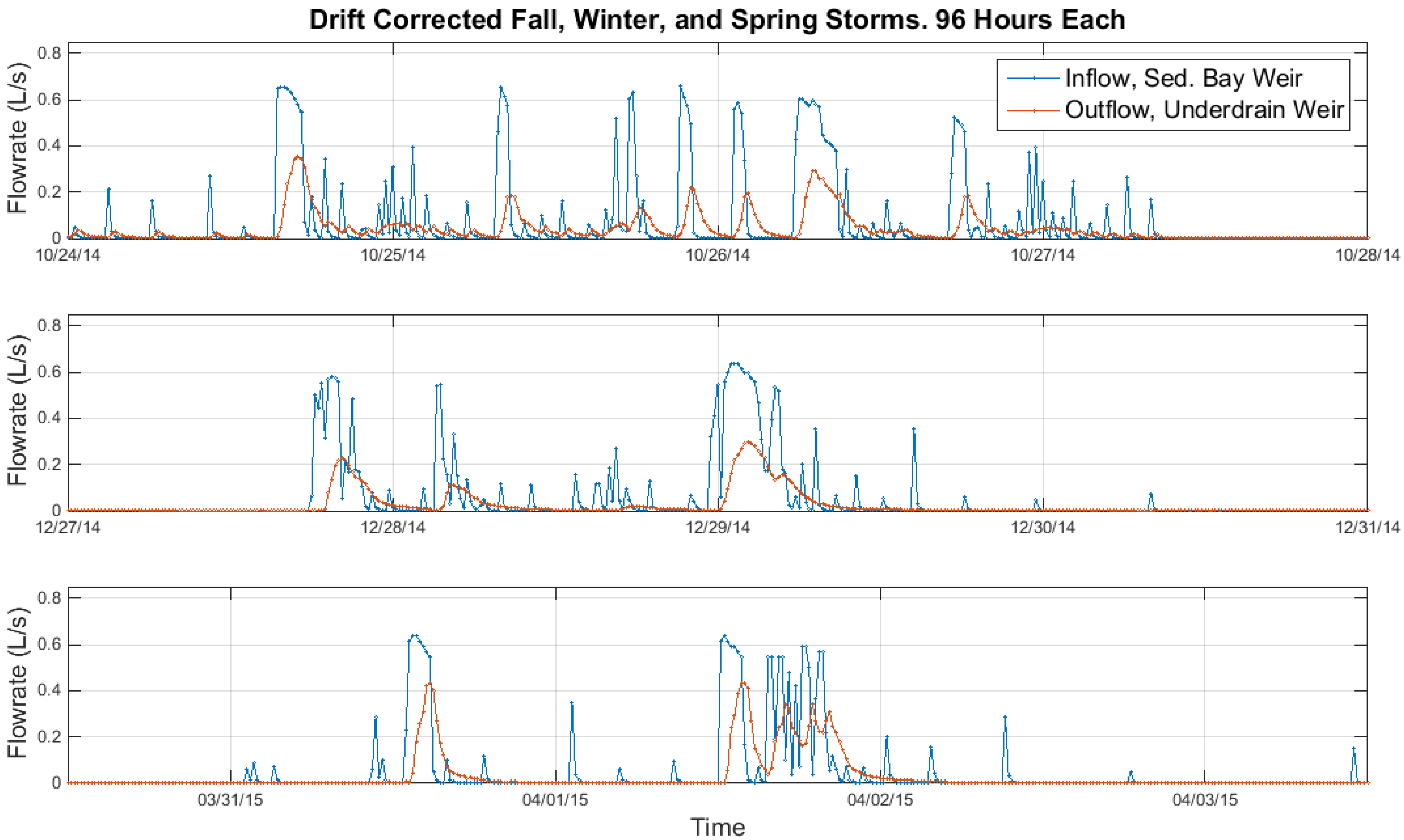

Figure 5.3 Drift corrected, pre-water balance calibrated flows. Storm events from fall 2014, winter 2014-2015, and spring 2015. The dots on the lines are data points collected at 15 minute intervals.

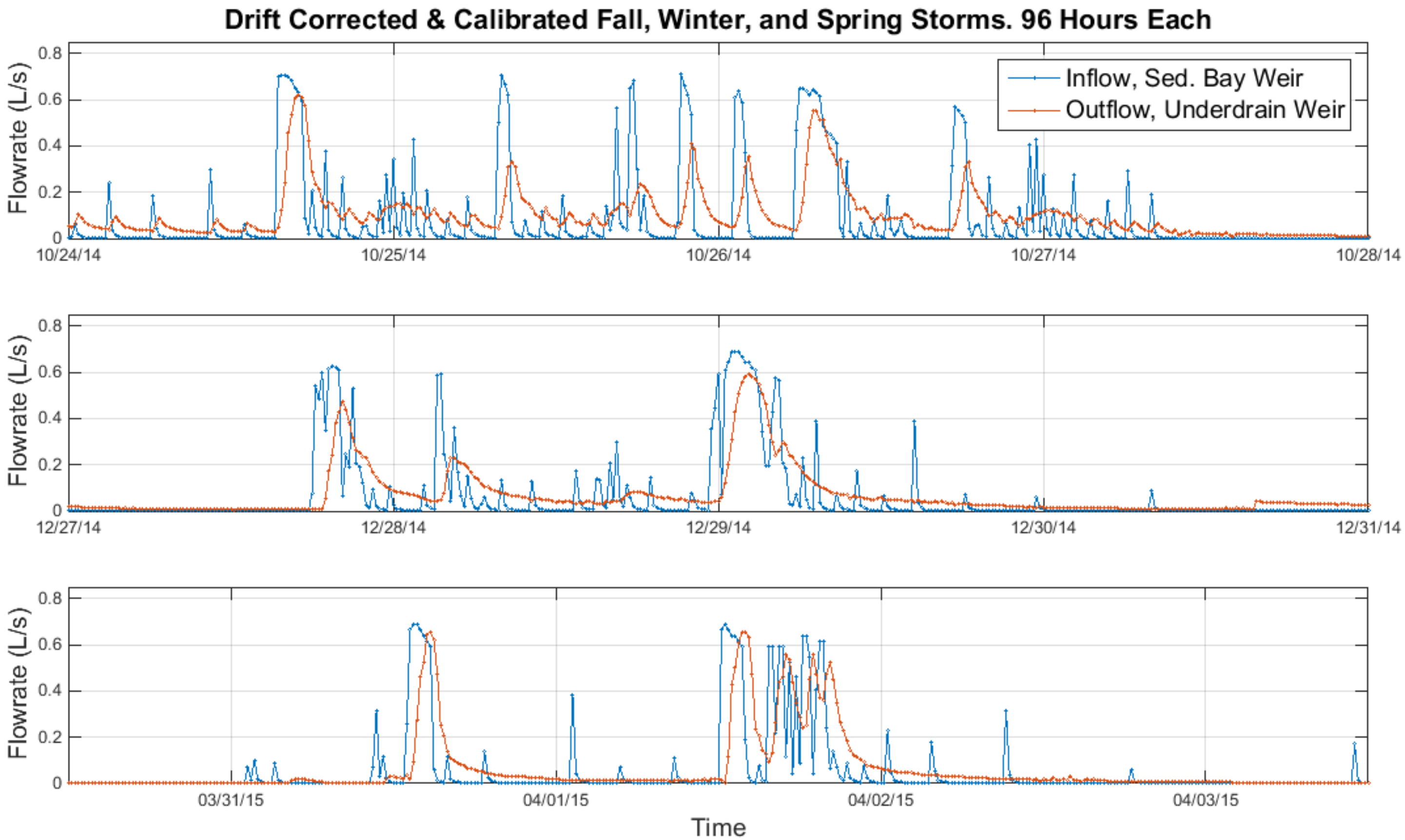

Figure 5.4 The drift corrected and water balance calibrated flow data were characteristic of the expected flow response: the water level drains to the bottom of the V before becoming relatively stable, and the outflow continues between peak flows due to gradual drainage of soil water.

The flowrate recession curve shapes followed the expected flow response in Error! Reference source not found.. The water levels drains to the bottom of V-notch weir before stabilizing at a relatively constant value, and outflow continues between peak flows due to a gradual drainage of soil water. Therefore, the drift correction and water balance calibration underdrain flow data for the three storm events was graphically validated.

<u>5.3 Peak Flow Response to Establishment Measured by Hydrologic Metrics</u>

Peak flow ratio and the peak delay metrics (**Eqn. 4.4 – 4.5**) and their statistics were calculated for the fall, winter, and spring seasons. An attempt to apply the calibrated h_{weir} values from the three storm events to the remainder of the drift corrected data was made, however the volume balance showed a greater outflow volume than inflow volume, indicating that a need for additional water balance calibrations were required before whole dataset could be rigorously validated. Therefore, the analyzed data set consisted of the water balance calibrated flow data from the three storm events along with the remainder of the drift corrected flow data that had not yet been water balance calibrated.

Matlab's built in "findpeaks.m" function was parameterized to find peaks for statistical analysis using the three storm events (Error! Reference source not found.). The following parameters were used to identify outflow peaks: a minimum outflow peak height of 0.1 L/s, a minimum time lapse between peaks of 1 hour, and a minimum peak prominence of 0.05 L/s. Inflow peaks were paired with outflow peaks by finding local maxima near outflow peaks.

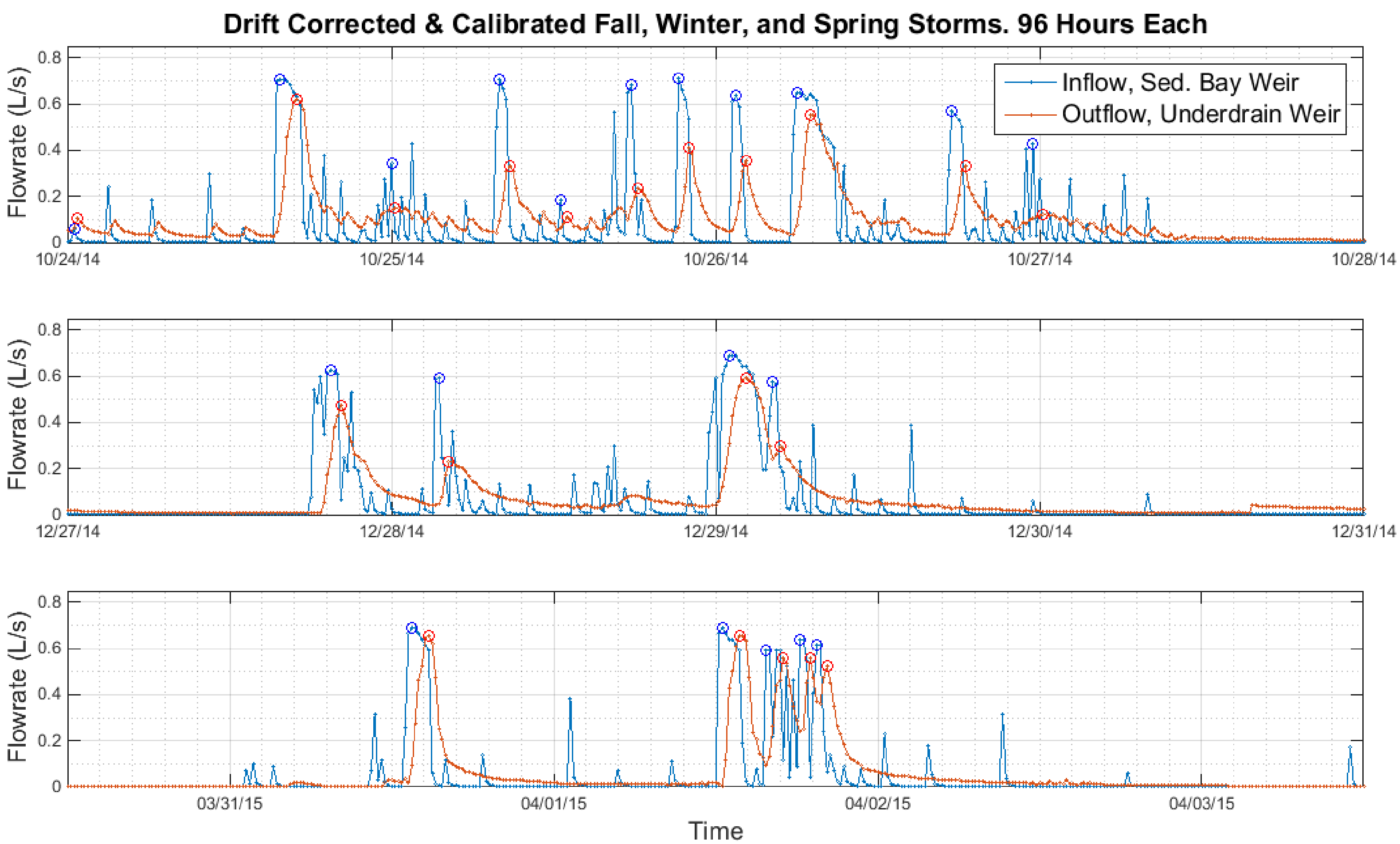

Figure 5.5 The peak finder was parameterized using the three storm events, and then it was used to find the peaks from the remainder of the drift corrected dataset.

The peak finder was then used to find peaks for the remainder of the dataset. A total of 64 peaks were paired for the fall, 23 for the winter, and 25 for the spring. Histograms of the peak metrics, see Error! Reference source not found. and Error! Reference source not found.**Error! Reference source not found.**, were used to verify the assumption of equal variance, and normal probability plots were used to verify normality. The distributions were considered to have similar spreads and be normally distributed, however, a larger data set and an improved peak finder would improve the validity of the Analysis of Variance (ANOVA) assumptions of equal variance, normality, and independence of observations.

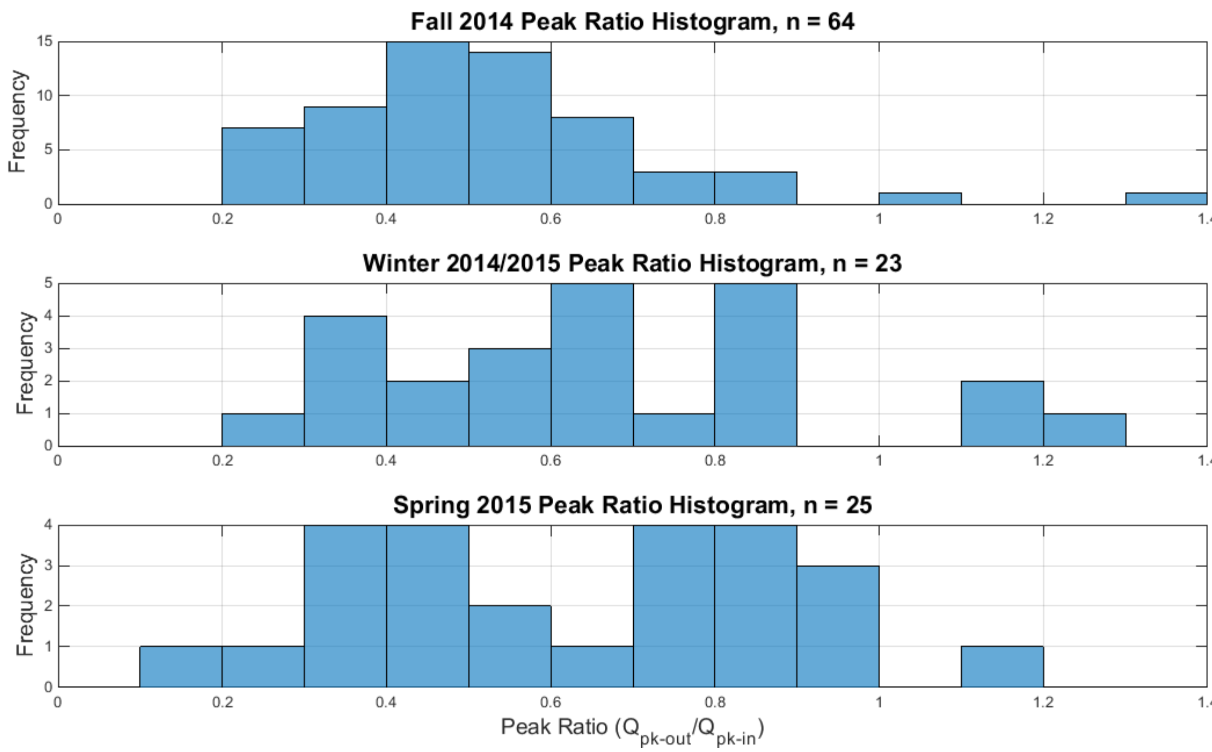

Figure 5.6 Histogram of peak ratio for each season. The distributions have a similar range of variance, which validates the assumption of similar spreads for the 1 way ANOVA.

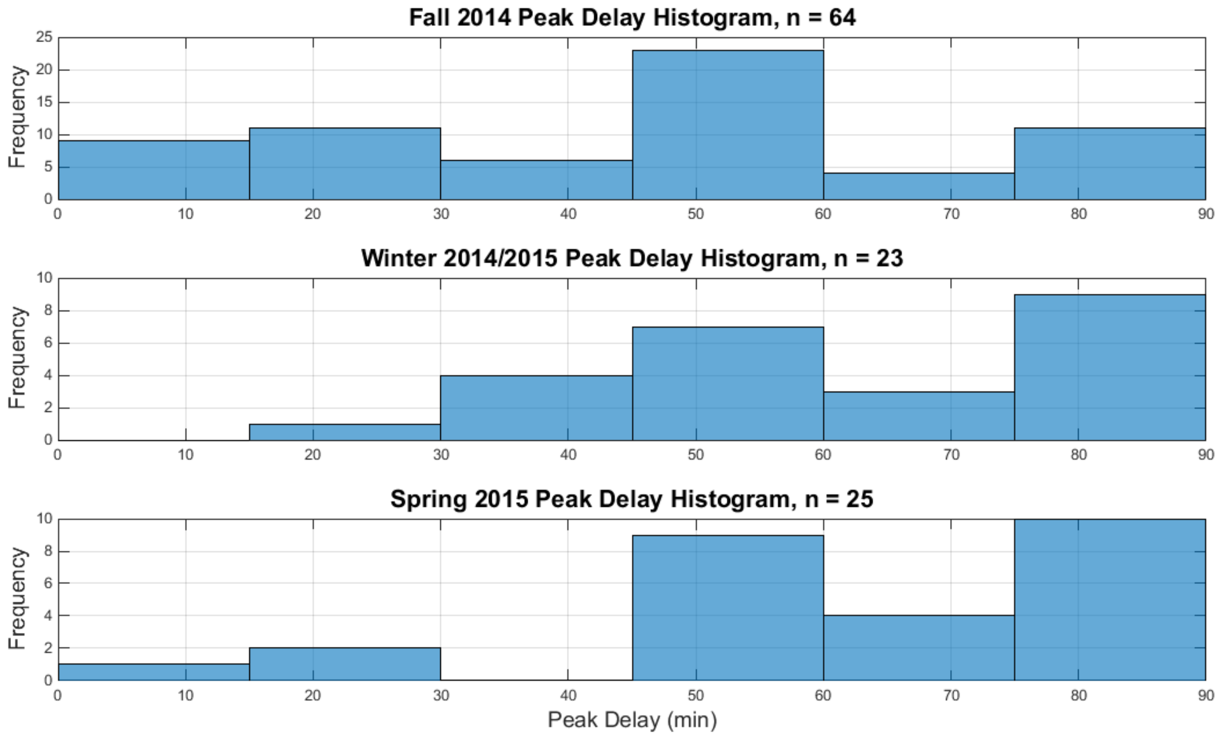

Figure 5.7 Histogram of peak delay for each season. The distributions have a similar range of variance, which validates the assumption of similar spreads for the 1 way ANOVA.

The mean peak ratio increased from 0.54 in the fall, to 0.68 in the winter, and then it decreased to 0.61 in the spring. The mean peak delay increased from 45 minutes in the fall, to 63 minutes in the winter, and then it decreased to 59 minutes in the spring. The p-values from the one way ANOVA on the peak ratio and peak delay, 0.090 and 0.0042, respectively, which do not indicate significantly different mean responses for the different seasons. See **Error! Reference source not found.** for a summary of the peak ratio and peak delay statistics. A trend of an increase in response magnitude followed by decrease was observed.

Table 5.4 Peak ratio and peak delay statistics. A one way analysis of variance indicates that the hydrologic performance metric means between seasons are not significantly different. However, a general trend of increased mean followed by decreased mean was observed for both the peak ratio and peak delay.

Peak Ratio (Q_{pk-out}/Q_{pk-in})			
Statistic	**Fall 2014**	**Winter 2014-2015**	**Spring 2015**
Mean	0.54	0.68	0.61
Median	0.51	0.63	0.61
Min	0.22	0.24	0.14
Max	1.69	1.25	0.95
Std. Dev.	0.25	0.27	0.25
Peak Ratio ANOVA			
F-Value	2.5		
P-Value	0.090		
Peak Delay (minutes)			
Statistic	**Fall 2014**	**Winter 2014-2015**	**Spring 2015**
Mean	45	63	59
Median	45	60	60
Min	0	30	0
Max	90	90	90
Std. Dev.	25	24	24
Peak Delay ANOVA			
F-Value	5.8		
P-Value	0.0042		
n	64	23	25

5.4 Drain Tests

A drain test was performed on November 9-10 and March 23-24. The results from the tests were plotted on the same figure for comparison (Error! Reference source not found.). The curves are characterized by a sharp peak followed by a gradual recession curve. The sharp peaks were produced immediately after the underdrain valve was opened. The majority of the head behind the weirs, $h_{measured}$, decrease in 15 minutes for Test #1, and decreased in 1 hour and 15 minute for Test #2. Test #2 is characterized by a more gradually slope recession curve than Test #1.

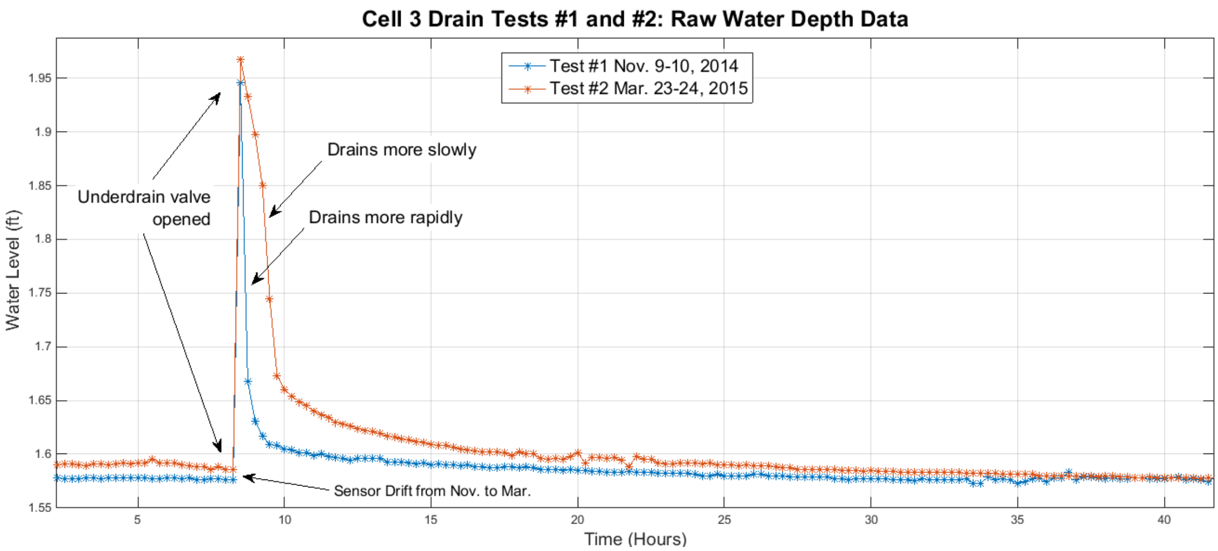

Figure 5.8 Results from the drain tests are characterized by sharps peaks followed by gradual recession curves. The recession curve in Test #2 had a more gradual slope than Test #1.

Chapter 6 Discussion

6.1 Pressure Transducer Drift Correction

The observed pressure transducer drift was detected by observations of the moving baseline for the water level at the bottom of the V-notch weirs following a storm event during which time $h_{measured} = h_{weir}$. Drift is common in fine level water measurement, and it tends to increase over time (Sorensen and Butcher 2011). The physical conditions exposed to the sediment bay pressure transducer were the following: after a storm event passed, the sediment bay water level decreased for approximately 2 hours until it reached the bottom of the V-notch weir. No additional flow into the bioretention cells was observed after approximately 2 hours. When the weather was warm and sunny, the water level in the sediment bay would continue to decrease after a storm at a rate slower than the first 2 hours due to evaporation. Therefore, storm events produced consistent patterns that were observed in the measured water level data. The baseline value for h_{weir} changed as frequently as from one storm event to the next, and possibly during the middle of a storm. When the value of h_{weir} changed, yet a similar storm pattern (due to the automatic pump) was observed, the pressure transducer drift was detected. Based on these patterns of the physical system, the value for h_{weir} was adjusted to account for the pressure transducer drift. However, the water balance was still not balanced after the drift correction, therefore further calibration of the value for h_{weir} was required, which led to the use of the water balance for calibration of h_{weir}. Therefore, while the drift correction improves the expected pattern of the water level response, it does not account for all of the error associated with the inflow and outflow calculations.

6.2 Water Balance Calibration

After the drift was corrected, the need for further calibration of the water level data was determined because the total cumulative outflow volume was only 59% of the total cumulative inflow volume. Greater confidence was given in the sediment bay water level data than the underdrain water level data because its water level response had fewer uncertainties to affect the measured water depth. The sediment bay water level measurement response was primarily affected by pumped inflow, direct precipitation, and a consistent pattern recession curve from the sediment bay drained out. The underdrain outflow response was affected by sediment bay weir inflow, direct precipitation, and an inconsistent recession curve pattern due to gradual drainage of water the soil. The inconsistent recession curve pattern was attributed to changes in the soil media during bioretention establishment. Therefore, the sediment bay water level response pattern was more uniform in time than the underdrain outflow response pattern, and greater confidence could be given in its pattern for calibration of the underdrain stilling well h_{weir} values.

The underdrain outflow water level was calibrated by adjustment of its height to account for the residual of the bioretention cell water balance for three 96 hour storm events during the fall, spring, and winter. The water balance was calculated using the vertex-adjusted inflow water level data, the Hargreaves method for ET estimation, precipitation data, and soil moisture data. After the calibration, the inflow and outflow data matched well with the expected response because their peaks and recession curves followed the expected flow model of a gradual decrease in water level to the bottom of the V-notch weirs. Nothing unusual, such as an outflow peak with a much greater magnitude than an inflow peak, or a recession curve that stabilized above zero, was detected in the calibrated dataset.

6.3 Bioretention Establishment

6.3.1 Peak Flow Analysis

The results of the peak flow metrics (Error! Reference source not found.**.4)** for each season were within the range of results reported by previous studies (**Table 2.1**). The mean peak ratio was 0.54 for the fall, 0.68 for the winter, and 0.61 for the spring, which falls into the literature value range of 0.01 to 0.86 (**Table 2.1**). The mean peak delay was 45 minutes for the fall, 63 minutes for the winter, and 59 minutes for the spring, which falls into the literature value range of 16 minutes to 309 minutes (**Table 2.1**). Therefore, the calculated means for the peak ratio and peak delay were similar to previous literature, and the bioretention cell studied here can be considered comparable to other bioretention cells.

The p-values for the ANOVA on the peak ratio and peak delay metrics were 0.090 and 0.0042 (Error! Reference source not found.**.4**), respectively, indicating a greater probability of a difference of means for the seasonal peak delay metrics than the seasonal peak ratio metrics. The inflow peak magnitude had a relatively consistent magnitude due to the automatic pump in the underground storage tank, and therefore the outflow peak magnitude could also be expected to have a relatively consistent magnitude. This explains the lack of significantly different peak ratio mean values throughout the monitoring period. The lower ANOVA p-value, and therefore greater confidence, of at least one season containing a different mean peak delay metric than the other seasons can be explained using the bioretention conceptual model.

The trend of an increase in mean peak delay from the fall to the winter followed by a slight decrease in the spring was observed. This trend is explained by the bioretention establishment conceptual model of initial soil compaction and clogging followed by preferential flow path development in the soil media. Previously work has shown a decrease in soil permeability followed by an increase over the course of 18 months (Hatt et al. 2009). The decrease in permeability was attributed to soil compaction due to hydraulic loading, and the increase was attributed to vigorous vegetation growth. Soil surface clogging due to stormwater sediment fines in the influent is also associated with decreased permeability. In (Greene et al. 2009), they found that permeability was greatest in bioretention treatments with vegetation and earthworms compared to their control treatment of bare soil.

The trend of the initial increase of the peak delay was hypothesized to occur due to a decrease in soil permeability. In this study, soil compaction was observed at the beginning of the establishment, especially during any activities that involved walking on the facility and after storm events. During planting and weeding activities, the compaction was observed to be greater at the surface than the subsurface. An accumulation of fine particles from the stormwater influent on the surface of the bioretention cell was also observed. The only data collected for the compaction and clogging were visual observation recorded in field notes.

The compaction and accumulation of fine particles corresponded with a decrease in permeability observed between the two drain tests. The drain test (Error! Reference source not found.) in March 2015, before substantial plant growth occurred, showed a milder sloped outflow recession curve compared to the November 2014 drain test. The milder sloped outflow recession curve was attributed to a lower rate of soil permeability. The moment that the soil surface becomes saturated is when ponding starts (Dingman 2014), and under soil conditions of low permeability, surface ponding occurs more readily. This explains the increase in peak delay because the soil surface becomes rapidly saturated due to compaction and clogging, which causes ponding, and allows for greater water storage at the surface from the inflow peak and increases the time until outflow peak arrival. Therefore, the observed trend of an increase in peak delay from 45 minutes in the fall to 63 minutes in the winter was attributed to a decrease of soil permeability caused by surface compaction and clogging.

Shortly after the second drain test in March 2015, the invasive weed species from the bioretention cell were removed by hand weeding, and the plants started growing vigorously (Error! Reference source not found.). The plant growth observed during the spring corresponds with the trend of the decrease in the mean peak delay from 63 minutes to 59 minutes, however the mean winter peak delay was not significantly different from the spring peak delay (one-tailed t-test, $p = 0.22$). There were more storm events earlier in the spring than later in the spring, therefore the peak flow data is more representative of an earlier stage of establishment in the spring. The length of this study was only 7 months, compared to Hatt et. al 2009 which was 18 months, indicating that further increases in soil permeability, and thus decreases in peak delay, are hypothesized to occur. Future drain tests and flow monitoring in the wet seasons of 2015 could be used to further validate the bioretention conceptual model after the summer growing months to determine if there is a greater response of the decrease of the peak delay.

6.3.2 Considerations for Future Research in Bioretention

The indefinite period of bioretention establishment time poses more questions than answers. There are two competing changes to the soil permeability. On one hand, the permeability may decrease as soil compaction and clogging are likely to continue to occur, although the compaction may stabilize, while the surface clogging increases due to a continuous influx of fines from urban stormwater runoff. On the other hand, the permeability may increase as the plants continue to grow their roots and earthworms and soil organisms continue to develop macropores and preferential flow paths, but this rate of development may approach zero as the soil reaches its carrying capacity. Therefore, in the long run, permeability could decrease, as the fines continue to accumulate, but the other factors effecting permeability stabilize. Long term research investigating how flows are affected by bioretention establishment will help to inform bioretention facility managers as to the type and schedule of maintenance activities required for meeting hydrologic objectives. Such activities may include replacement of the top several cm of soil media, or re-vegetation efforts to maintain desired permeability.

Figure 6.1 Photos of plant growth throughout the monitoring period.

6.4 Error Analysis

6.4.1 Flowrate Calculations

The drift corrected and water balance calibrated water level datasets were sources of error for the peak flow metric analysis. The peak ratio was subject to greater error than the peak delay because the peak ratio depends on the magnitude of the peaks, while the peak delay only depends on the relative location of the peaks. The peak flow magnitudes, which were used for the peak ratio calculations (**Eqn. 4.4**), were subject to error from the water level measurements. The accuracy of each of the pressure transducers measured water depth are specified in the methods; a value of $\pm$ 3.8mm (the 1.5m range SDX) was used for the following analysis.

The error associated with the pressure transducer reporting a value lower than the true value is the under measured depth, and error associated with the pressure transducer reporting a value higher than the true value is the over measured depth (Error! Reference source not found.).

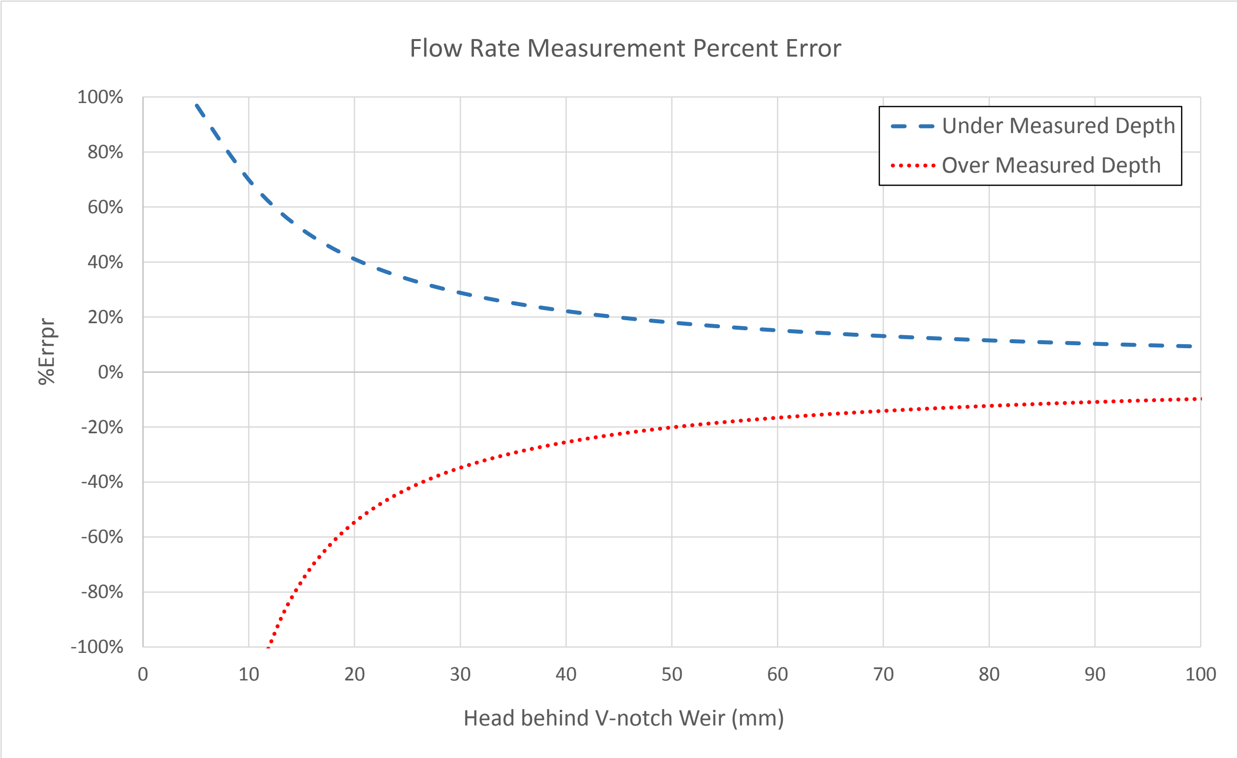

Figure 6.2 Variation of error with water depth for the inflow rate measurements. The error decreases exponentially as the head behind the V-notch weir increases.

The flow rate calculation error decreases exponentially as the value of head of water behind the weir, h_V, increases. The mean inflow peak magnitude was 0.59 L/s, which corresponds to an under measured depth error of 15% and an over measured depth error of 16% of the true value. The mean outflow peak magnitude was 0.43 L/s, which corresponds to an under measured depth error of 16% and an over measured depth error of 18% of the true value. The error associated with sediment bay water level measurements for the inflow calculations at the pump's full capacity of approximately 0.75 L/s per cell was 13% to 14% of the true value.

An example of how the 1.5m range SDX pressure transducer accuracy of 3.8mm affects the flow rate measurements can be seen in Error! Reference source not found..

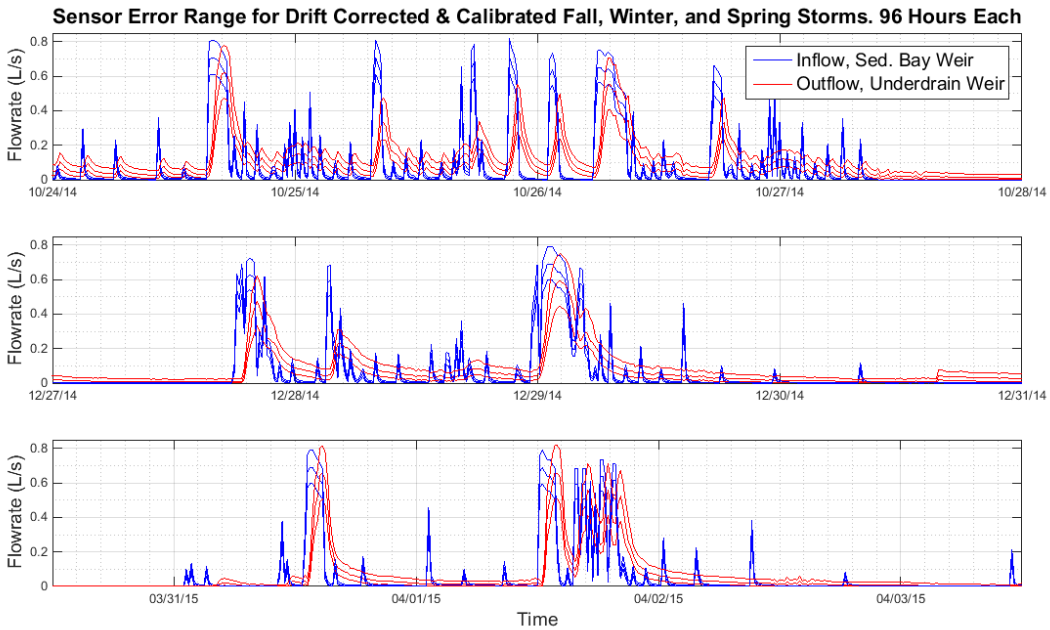

Figure 6.3 The range of error for the inflow and outflow measurements based on a 3.8mm accuracy of the 1.5m SDX pressure transducers. The red lines bound the inflow rate error, and the blue lines bound the outflow rate error.

A greater magnitude of error occurs for the underdrain outflow measurement because the peaks were generally of lesser magnitude and the geometry of the compound weir with a 2.5cm 90° V-notch and 7.6cm rectangular weir configuration is such that a smaller change in water depth is associated with a greater change in flowrate measurement.

6.4.2 Additional Sources of Pressure Transducer Measurement and Flow Calculation Error

A study that investigated the error of 14 leading brand pressure transducers for fine water level measurement in the field found that the typical accuracy was reported as about $\pm$ 10mm, and that measurement drift ranged from negligible to 27 mm for their 100 day monitoring period (Sorensen and Butcher 2011). Another study that investigated the correlation between measured sensor error and temperature in vented pressure transducers found that the noise in the measurement increased as temperature increased under both laboratory and field conditions (Liu and Higgins 2015). While the three storms that used drift corrected and water balance calibrated data for flowrate calculation were graphically validation, a more rigorous study aimed at investigating sensor error would improve the confidence in these methods. The drift correction and water balance calibration methods were not an anticipated outcome of this study, therefore, the only validation for these methods was based on data that had already been collected.

The drift correction error could be reduced by using physically measured values of h_{weir} with a staff gauge before and after every storm event. Additionally, investigation of the relationship between atmospheric pressure, vented tube length, and pressure transducer reading may allow for the development of additional methods to improve the drift correction. Finally, more accurate water level data could be measured with higher quality pressure transducers and with shorter time-steps between measurements, or an increased scanning and reporting time, to reduce the error in the fine water level measurement.

The water balance includes multiple sources of data, including Hargreaves method for evapotranspiration estimates, precipitation data, and soil moisture data, and each one of these sources of data influences the water balance calibration. However, both the evapotranspiration and precipitation were an order of magnitude smaller than the inflow and outflow data, so the error associated with the use of these data for the water balance was negligible. However, the estimated volumetric change in soil moisture content was on the same order of magnitude as the inflow and outflow data for the fall, winter, and spring storm events. This source of error in the water balance calibration could be addressed with additional soil moisture sensors to improve the estimate for volumetric soil moisture content.

In this particular bioretention facility setup, a second water balance that uses the precipitation data along with water level data in the underground storage tank and a runoff and pump model could be used to further validate the calibration of h_{weir} for the sediment bay inflows. Greater confidence could then be put into the sediment bay inflow volume for the water balance calibration of the underdrain h_{weir} value.

Another possible source of error is in the weir equation used for the inflow measurement and the rating curve used for the underdrain outflow measurement. V-notch weir thickness should be between 0.79mm (1/32 in.) and 1.6mm (1/16 in.) (Shen 1981). The inflow weir is made of 6.4 mm (1/4 in.) stainless steel, therefore the applicability of the v-notch weir equation for this thickness of weir is questionable. A flume experiment with the sediment bay v-notch inflow weirs could be used to develop a rating curve to check the accuracy of the V-notch weir equation. The discharge table developed by Thel-Mar was linearly interpolated to account for measured values not included in the discharge table, and the manufacture's specified flowrate accuracy was 5%. The methods the manufacturer used to determine this accuracy are unknown, therefore, the accuracy of the Thel-mar weir could also verified with a flume experiment.

Chapter 7 Conclusions and Recommendations

A bioretention cell was monitored for peak flow response to bioretention establishment between October 2014 and May 2015. The fine water level sensor measurements were observed to drift by as much as 29 mm over 93 days, and a novel method for drift correction was applied to fix the drift. Further calibration of the flowrate calculations for three storm events was completed using a water balance approach. The results of the drift correction and water balance calibration were graphically validated to follow the expected pattern of a decrease in water level to the bottom of the v-notch, followed by a period of water level stabilization.

Peak flow metrics of peak ratio and peak delay were calculated for the fall, winter, and spring of the monitoring period to evaluate the peak hydrologic response of bioretention establishment. The mean peak ratio was 0.54 in the fall, 0.68 in the winter, and 0.61 in the spring. The mean peak delay was 45 minutes in the fall, 63 minutes in the winter, and 59 minutes in the spring. A p-value of 0.090 for the peak ratio and 0.0042 for a 1 way ANOVA indicated that there was a greater probability that at least 1 season had a different mean peak delay than peak ratio. The trend of an increase in peak delay from fall to winter was attributed to changes in soil permeability caused by soil compaction and clogging. This trend was further supported by changes in permeability observed during a drain test in November and March. A weak trend of a decrease in peak delay from winter to spring was attributed to preferential flow path development caused by plant roots. However, the peak ratio and peak delay metrics should be considered with caution due to the minimal validation of the drift correction and water balance calibration methods. Future work should attempt to minimize error in water level measurements for flow rate calculations, validate the drift correction and water balance calibration techniques, and use a longer term dataset to determine if there is a stronger response in the peak delay during the next wet season after the plants and soil continue to mature throughout the summer.

Bioretention establishment hydrology is important to consider in bioretention design as these systems continue to be improved to meet hydrologic function objectives for both flood control and restoration of pre-development hydrologic regimes. The results of this work emphasize the importance of water level measurement validation when using weirs and pressure transducers for flow rate calculations, which is common in the bioretention literature. While the results of this study weakly suggest that peak flows are affected by bioretention establishment, further research is needed to quantify the extent of the establishment and its role in peak flow hydrology.

7.1 Technology Transfer

The main product of the project is a new state-of-the-art testing facility that can be used for assessing the effectiveness, in terms of water quality improvement and peak flow reduction, of green infrastructure practices for improving storm water management on roadways. This facility has three independent cells and is isolated from the groundwater table. The facility is already being used and there is ongoing conversations with regional stakeholders for its long-term use. We anticipate that this state-of-the-art facility will be widely used by stormwater stakeholders, including the Oregon Department of Transportation, who may fund a project to use this facility through their research office. In the last few years, researchers are amassing a body of evidence to prove that green infrastructure works: these systems are shown to be more cost-effective than outmoded models of grey infrastructure, and also provide far more benefits for both people and the environment. The newly developed laboratory will be used to test new technologies that can make green infrastructure systems even more cost-effective.

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Appendix A: Plant List

	Plant Species	Intentially Added?
1	*Achillea millefolium*	x
2	*Camassia quamash*	x
3	*Carex densa*	x
4	*Carex obnupta*	x
5	*Danthonia californica*	x
6	*Deschampsia cespitosa*	x
7	*Eschscholzia*	
8	*Fragaria virginica*	x
9	*Gaultheria shallon*	x
10	*Juncus patens*	x
11	*Lupinus polyphyllus*	x
12	*Mahonia repens*	x
13	*Matricicaria discoidea*	
14	*Mimulus guttatus*	x
15	*Potentilla gracilis*	x
16	*Rosa nutkana*	x
17	*Saxifraga oregana*	x
18	*Scirpus acutus*	x
19	*Sidalcea campestris*	x
20	*Symphoricarpos albus*	x