PROCEEDINGS

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QUANTIFYING THE HYDROLOGICAL PERFORMANCE OF EXTENSIVE VEGETATIVE ROOFS

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ABSTRACT

The Green Roof Innovation Testing (GRIT) Lab at the University of Toronto is a multiyear research project comparatively analyzing 33 extensive green roof modules with variables of composition and maintenance. Each module is continuously monitored through an array of nine thermal and hydrological sensors.

This presentation will focus on the troubleshooting and calibration processes of two sensors contributing to the hydrological modeling of the modules. These processes involved analyzing the dielectric permittivity of the two growing substrate types, as well as designing and fabricating new components of the instruments.

The presentation is directed to a range of industries and professionals concerned with green roof design, construction, maintenance, and monitoring and sits in the beginner to intermediate range.

SPEAKER

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MATT PEROTTO and CATHERINE YOON are third-year thesis students of the Master of Landscape Architecture program at the University of Toronto. They each hold a BES in Honors Planning with a specialization in Urban Design from the University of Waterloo. Over the last two summers, Matt and Catherine worked as research assistants at the GRIT Lab, where they were responsible for the collection and organization of data, troubleshooting and calibration of sensors, and maintenance and daily operations of the laboratory.

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JENNY HILL is currently undertaking a PhD in Environmental Civil Engineering at the University of Toronto. Her research into the resiliency of infrastructure in the face of climate change includes measuring the hydrological performance of vegetated roof installations. Jenny is collecting data at the GRIT Lab to assess the suitability of percolated water for subsequent irrigation and is using analytical techniques to calibrate a water balance model for use in the field.

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ABSTRACT

The Green Roof Innovation Testing (GRIT) Lab at the University of Toronto is a multiyear research project comparatively analyzing 33 extensive green roof modules with variables of composition and maintenance. Each module is continuously monitored through an array of nine thermal and hydrological sensors.

This presentation focuses on the troubleshooting and calibration processes of two sensors contributing to the hydrological modeling of the modules:

1. Decagon 5TE moisture sensors embedded within the planting substrate
2. Hydro Services TB6 rain gauge, measuring water volume drained through each module

Each of these sensors was designed for slightly differing applications, and thus needed modification to accommodate the specific conditions of the research project.

The calibration process involved pairing substrate moisture with the dielectric permittivity of the two planting substrate types in the modules and designing, fabricating, and testing new components of the rain gauges.

Since installation, the recalibrated instruments have been providing the GRIT Lab with accurate data since August 2013.

Learning objectives will include:

- A comparison of substrates used in green roof construction
- The relevance in monitoring green roof performance in research and practice
- The role of instrument calibration
- An analysis of calibration processes of research instruments.

GREEN (VEGETATIVE) ROOFS

Green (or vegetative) roofs are one of the fastest-growing sustainable technologies implemented across the world today (Green Roof Technology, 2014). An ever-expanding body of research continues to quantify the environmental benefits of green roofs with regard to stormwater management (K. Liu, 2002), energy conservation, and habitat development (Oberndorfer et al., 2007). This paper provides detailed insight into various methods by which these findings are quantified through an exploration of the processes behind calibrating instruments used in the primary monitoring of such performance.

Vegetated roofs have been documented throughout history, with the first forms of roof gardens dating back to nearly 500 BC (BCIT, 2012). Modern green roof design, characterized by a system of building membrane, planting substrate, and vegetation, was not fully developed until the 1960s in Germany. In an effort to conserve energy as a response to the energy crisis in 1973, lightweight adaptations of this new technology were explored (Oberndorfer et al.). This resulted in the development of "extensive green roofs"—systems that are lightweight, have low plant diversity, and require minimal maintenance.

The extensive green roof construction process commonly includes stacking several layers of materials to ensure the functionality of the system and safety of the building. These include (but are not limited to) structural support, roof membrane, insulation, drainage/storage layer, filter fabric, planting substrate, and a vegetated layer of specific plant communities (Peck and Kuhn, 2003). Extensive green roofs requiring little maintenance are often desirable, as most are inaccessible, typically limiting plant selection to drought-resistant species.

There are advantages and disadvantages to extensive green roofs. First, extensive green roofs are lightweight, making them much easier to retrofit onto existing buildings, which are evaluated prior to installation to ensure the structure can support the weight of the green roof. They vary between 10 and 35 pounds per square foot of roof load (Getter and Rowe, 2014). As the height and volume of planting substrate increases, more void space for water retention becomes available. As the volume of water suspended within the planting substrate rises, the net weight of the system responds proportionally. Many extensive systems are modular in their product specification and design, making them easy and efficient to install, and therefore, more cost-efficient (Getter and Rowe, 2014).

CITY OF TORONTO

In May of 2009, the City of Toronto issued a bylaw and supplementary construction standards requiring all new developments greater than 2,000 square meters in gross floor area (GFA) to install a green roof. The required size of the green roof begins at 20% of the roof's surface and goes up to 60% if the building is over 20,000 square meters in GFA (Council of the City of Toronto, 2009). This bylaw was the first of its kind in North America. It plays a pivotal role in the development and construction industry in the City of Toronto, as Toronto currently has the most high-rise buildings under construction on the continent (Perkins, 2012).

Prior to the adoption of the Green Roof Bylaw, there was no sufficient or ongoing research on green roof performance specific to Toronto's climate and global context. As a result, many of the specifications outlined in the construction standards were developed from specifications prepared by the German professional association, Forschungsgesellschaft Landschaftsbau Landschaftsentwicklung (FLL), which in English is The Landscaping and Landscape Development Research Society.

GREEN ROOF INNOVATION TESTING LABORATORY (GRIT LAB)

The Green Roof Innovation Testing Laboratory (GRIT Lab) was the first and only research laboratory in Toronto that predated the Green Roof Bylaw (Banting et al., 2005). The GRIT Lab was developed to test the standard industry practices common to the greater Toronto area prior to the bylaw with the purpose of determining what combination of materials performs best with respect to water, energy, and plant cover and diversity.

The research lab is designed to test four different parameters of construction and maintenance on 33 separate test beds

Figure 1 – View of the GRIT Lab research facility showing all 33 green roof bed modules.

Property (ASTM E2399-11)	Organic	FLL-compliant
Saturated hydraulic conductivity (cm/s)	> 0.01	> 0.02
Maximum water-holding capacity (%)	> 60	45
Max. substrate density at saturation (g/cm^3)	1.10	< 1.28
Dry density (g/cm^3)	0.58	> 0.8

Figure 2 – Specifications of the two planting substrate types tested at the GRIT Lab (as reported by manufacturer).

(see *Figure 1*). These variables include two types of planting substrate, two substrate depths, three plant communities, and three alternative irrigation regimes. Some of these materials are typical to existing green roofs of the region and are specified by the FLL, while others are native and locally sourced as recommended by Banting et al. in 2005. The GRIT Lab aims to quantify the performance effects of these recommendations.

The GRIT Lab analyzes the effects that different combinations of these variables have on the following common measures of green roof performance:

- Hydrology
  - — Stormwater retention
  - — Reduction in peak flow
  - — Delay of peak flow
  - — Sub-zero performance
- Thermography
  - — Evaporative cooling
- Environmental
  - — Biodiversity
  - — Plant biomass
  - — Pollinator species diversity

PLANTING SUBSTRATE

The GRIT Lab compares the performance of two different planting substrates. The first, “FLL,” is a specific blend designed to comply with the recommendations from the FLL association and is often used to support succulent plants, specifically sedum communities. It contains very low organic content and is high in aggregate construction slag of varying particle sizes. The bulk density of the FLL substrate is reduced by the inclusion of lightweight expanded aggregate; and as such, it is free-draining. This planting substrate comes at a high-embedded energy cost due to

Parameter	Position	Instrument
Surface temperature	120 cm above substrate	SI-111 infrared radiometer, Apogee
Temperature	60 cm above substrate	100K6A thermistor, Betatherm
	15 cm above substrate	100K6A thermistor, Betatherm
	Substrate surface	100K6A thermistor, Betatherm
	Bottom of substrate	100K6A thermistor, Betatherm
	Beneath the green roof module	100K6A thermistor, Betatherm
Volumetric water content	Mid depth of substrate	5TE sensor, Decagon Instruments
Electrical conductivity		
Soil moisture tension	Mid depth of substrate	Custom-built tensiometer, Irrometer
Stormwater runoff	Beneath the green roof module	TB 6 tipping bucket rain gauge, Hydrological Services

Figure 3 – Instruments used in the GRIT Lab green roof modules.

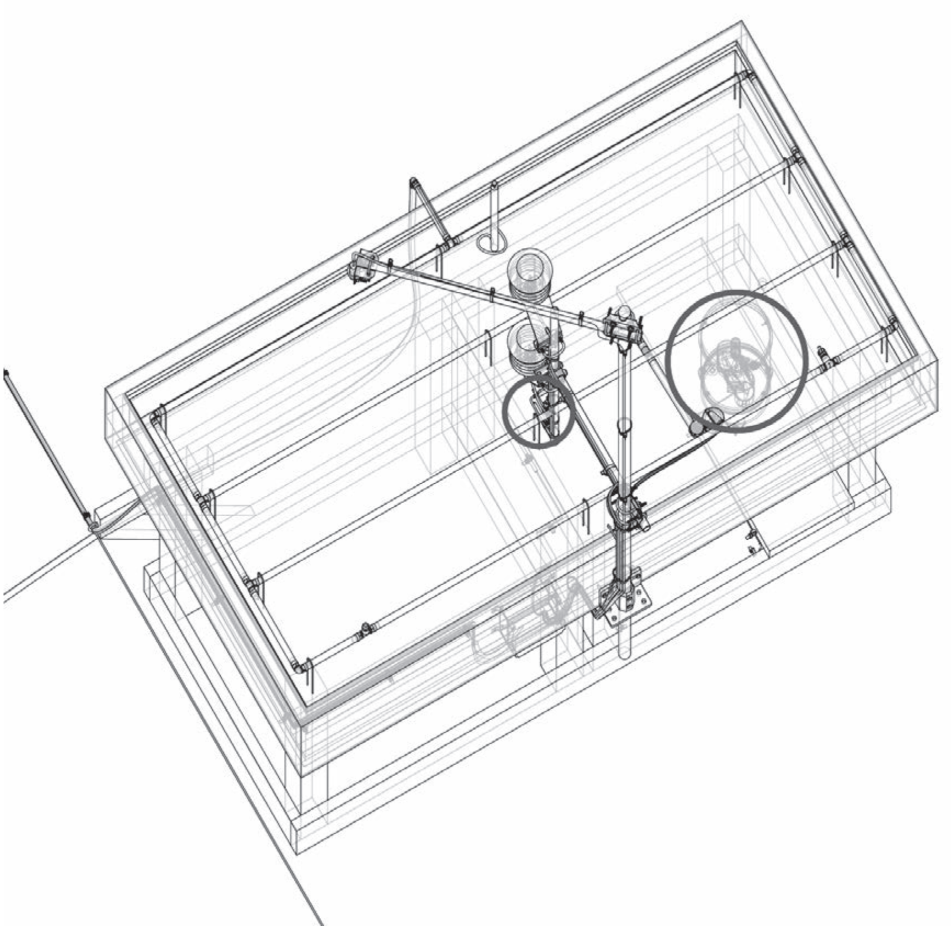

Figure 4 – Array of instruments used in the GRIT Lab green roof modules.

the specialized manufacturing process and affixed lengthy transportation. The second, "organic" planting substrate is designed to support a wide range of vascular plants and contains a high proportion of compost. The increase in organic matter contributes to a reduced bulk density from typical topsoil. The high organic content also contributes to increased capacity for water retention. A more detailed description of the planting substrate is given in *Figure 2*.

HYDROLOGICAL SENSORS AT THE GRIT LAB

Research and data analysis at the GRIT Lab relies heavily on sensors that automate the collection of data. Each of the 33 test beds contains nine sensors, all of which record measurements every five minutes (see *Figure 3* and *Figure 4*). The GRIT Lab also contains a weather station that measures ambient environmental conditions (See *Figure 5*). This allows for data to be compared both between individual beds, as well as as with average climactic conditions. The remainder of the paper is dedicated to a discussion of two of the sensors used in the research lab with regard to their function, operation, and calibration.

The sensors used to monitor the water content within the substrate and the tipping buckets used to measure discharge flow were both unsuitable to be used directly in the condition in which they were purchased because they are both made for agricultural purposes dissimilar to the context of our research. These issues are described in more detail in the following sections. Calibrating both proved critical to meet the needs of the lab, as they contribute to defining the water balance equation for each of the green roof bed modules. This evaluates the amount of water entering the green roof module in comparison to the amount of water percolating through it. The difference in volumes and flow rates between these two explicitly measured values can then be attributed to the hydrological performance of the green roof bed (Berndtsson, 2009).

Green roof planting substrates (and natural soils) are heterogeneous mixtures made up of a variety of materials, particle sizes, and void spaces. Each one of these materials has a different dielectric permittivity (Wang and Schmugge, 2007). The 5TE water content sensor, by Decagon Devices, uses an indirect method to calculate volumetric water content (VWC) within the planting substrate through dielectric permittivity. As a 70-MHz oscillating wave is sent through the sensor prongs, the sensor becomes charged according to the dielectric properties of the surrounding material (see *Figure 6*). It then generates a reading of bulk dielectric through summing the products of the dielectric of each individual material with its corresponding volume (these materials include air, soil minerals, organic matter, ice, water, etc.).

Bulk dielectric is related back to VWC through a specific calibration, which solves for volume of water in a known volume of soil. VWC is a critical component of the water balance equation as it describes the amount of water physically suspended between particles within the planting substrate. This method is common practice for informing VWC measurements (Decagon Devices Inc., 2014). The 5TE sensors are initially calibrated for "normal mineral soil" with an expected margin of error within ±3% VWC (Decagon Devices Inc., 2014). The two planting substrate types described in the preceding sections do not exemplify similar characteristics to such natural mineral soils found in agricultural applications.

Parameter	Instrument
Wind Speed	Wind monitor 05103, R.M. Young
Wind Direction	
Solar Radiation	CMP 11 pyranometer, Kipp and Zonen
Temperature	HMP45C thermal and humidity probe, Campbell Scientific
Relative Humidity	
Barometric Pressure	
Rain Gauge	TE525M tipping bucket rain gauge, Texas Electronics

Figure 5 – Instruments used in the GRIT Lab weather station.

Tipping bucket instruments are used to measure the amount of water draining through the bed through a frequency-based logger. The physical operation of the mechanism is simple: Water falls into a funnel, through a nozzle (also known as a syphon body), and into a see-saw that tips when filled with a prescribed amount of water—for example, every 6.28 mL of water (see *Figure 7*). Each tip is recorded through interaction of a permanent magnet with an internal reed switch. The switches are connected to a data logger, allowing for automated data collection. This measurement is critical to defining the water balance equation with regard to both volume and flow rate, and it allows us to immediately witness variation between water entering and water discharging from the bed.

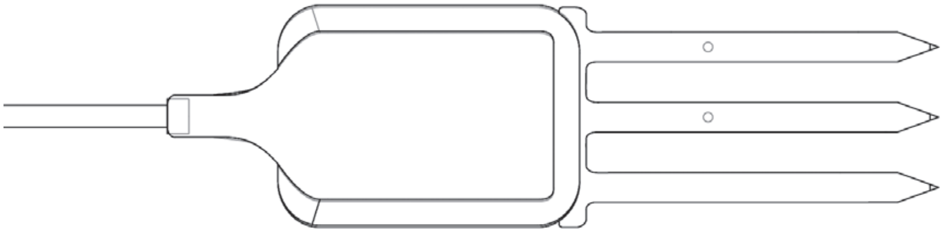

Figure 6 – The water content sensor.

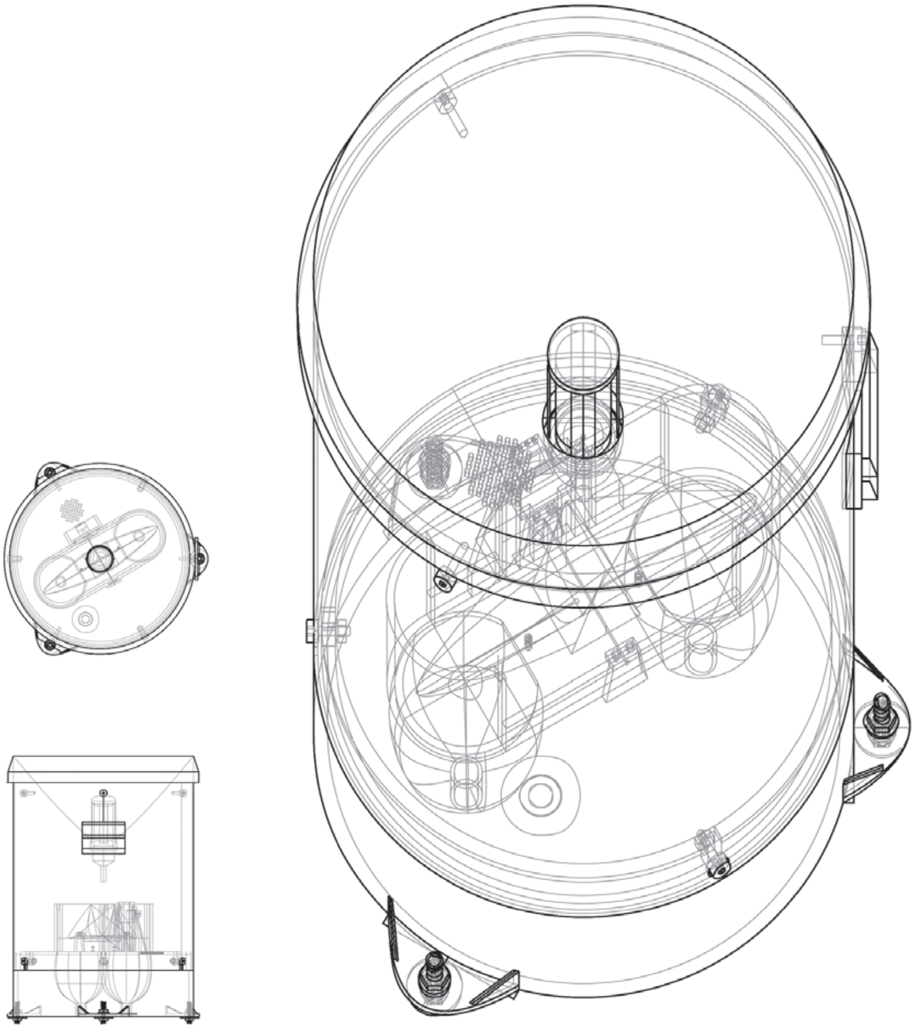

Figure 7 – The tipping bucket instrument.

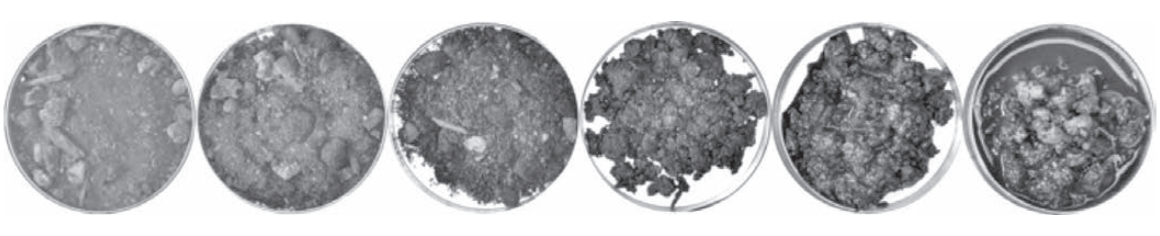

Figure 8 – Mineral substrate (FLL-compliant) prepared with increasing degrees of saturation from left to right. Note that the final sample is above the saturation capacity of the material.

The TB6 tipping bucket, by Hydrological Services, is commonly used to measure rainfall and precipitation in remote and open, unattended locations (Hydrological Services, 2009). At the GRIT Lab, however, the TB6 gauges receive a much heavier and more concentrated amount of water from the green roof modules. This is because they are measuring water collected from an area of 2.88 m^2, not the 0.03 m^2 area that they were designed for. The increase of this extra drainage area resulted in volumes and flow rates too large to pass through the nozzle without backing up within the funnel. During extreme events, drainage water would overflow from the collecting funnel of the instrument without being captured and measured by the instrument.

Both the 5TE and the TB6 are used to understand how long water is retained in the planting substrate after a storm or irrigation event and how much water is discharged, and to provide an indication of how much water evapotranspires after being retained within the green roof. Through a comparative analysis of these measurements of the different beds, the GRIT Lab is able to find correlation between materials and maintenance and their related effects on hydrological performance.

METHODS

Soil Moisture Sensor

The recalibration process for the 5TE sensors was undertaken in accordance with the manufacturer's directions (Chambers, 2011). A volume of the green roof planting material was air-dried before using the 5TE sensor to record the dielectric permittivity in triplicate. Two samples of this material were then weighed and air-dried to determine the corresponding water content. A portion of water is mixed into the bulk volume of the planting substrate and rested to equilibiriate the water content throughout before the test is conducted again. This entire sequence is repeated until the planting material is fully saturated (*Figure 8*).

Tipping Bucket Sensor

The existing nozzles were measured and modeled in Rhinoceros, a 3-D modeling software, which permitted virtual iterations of the nozzle diameter to increase the flow rate. Five diameters were then selected, and a prototype for each was produced in ABS plastic using fused deposition modeling (Dimension 1200es). The prototypes were tested for flow rate and unusual flow characteristics before confirming the final dimensions (See *Figure 9*).

RESULTS AND DISCUSSION

Soil Moisture Sensors

The organic planting substrate demonstrates similar characteristics to the original manufacturer's calibration (see *Figure 10*), although the steepness of the curve shows that greater substrate water content is required to give the same dielectric permittivity. This may be due to the larger compost particles having less intimate contact with the probe.

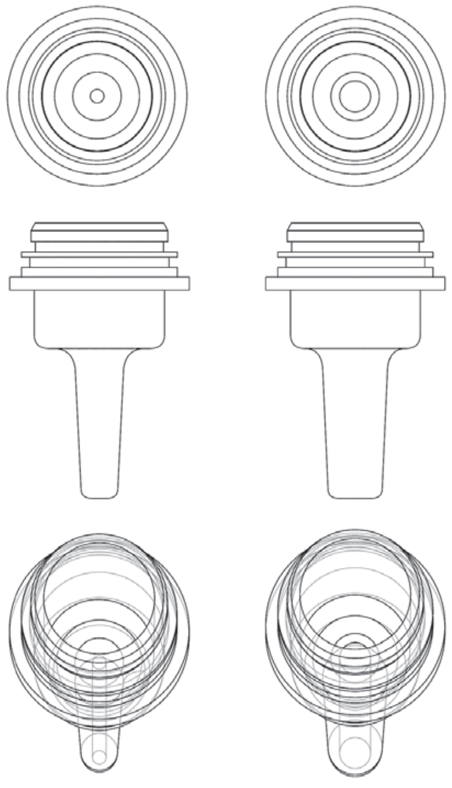

Figure 9 – The tipping bucket nozzle.

In comparison, the mineral-based FLL behaved quite differently (see *Figure 11*). It retained only two-thirds of the water volume before becoming fully saturated, so that water ran out (0.4 vol/vol in *Figure 11*, versus 0.6 vol/vol in *Figure 10*).

The fitted S-shaped curve is also distinctive compared to the curves in *Figure 10*. This is due to the intra-particle pore spaces, which absorb water like small sponges, preventing an increase in the dielectric permittivity at low water levels. Once these mineral sponges are filled with water, any additional water rapidly increases the conductivity until the saturation point is reached. The overall lower water retention capacity and sudden upward inflection in the curve in *Figure 11* result from a low proportion of fine particles in this planting substrate blend.

Tipping Bucket Sensors

As expected, a linear trend was observed between the internal cross section of the nozzles and the flow rate of the water (see *Figure 12*). Based on the practical requirements of the green roof experiment, a maximum flow rate of 12 liters in five minutes was anticipated. Using the graph in *Figure 12*, an optimal cross section area of 32 mm (translating into a diameter of 6.4 mm) was chosen for production. A total of 33 nozzles were fabricated using the same 3-D printing technique and were installed on each of the instruments.

CONCLUSION

Most green roof research in the North American context is centered on testing the components of the FLL association guidelines—aggregate heavy-planting substrate such as the FLL used at the GRIT Lab with sedum plant communities. Municipalities, politicians, decision-makers, and architects

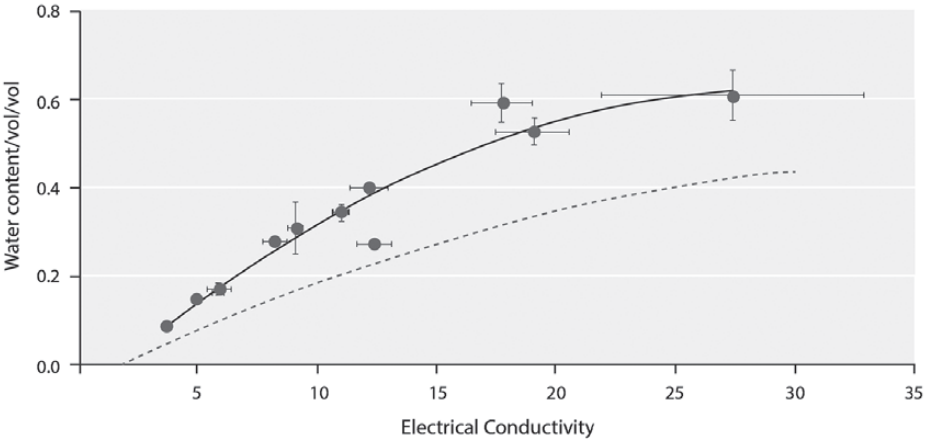

Figure 10 – Results from the recalibration of the 5TE sensor in the "organic" planting substrate. The original calibration is shown as a dashed line.

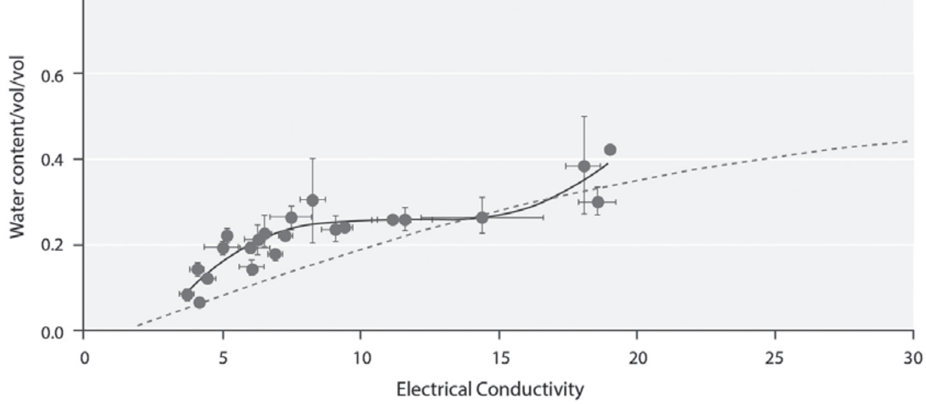

Figure 11 – Results from the recalibration of the 5TE sensor in the "FLL" planting substrate. The original calibration is shown as a dashed line.

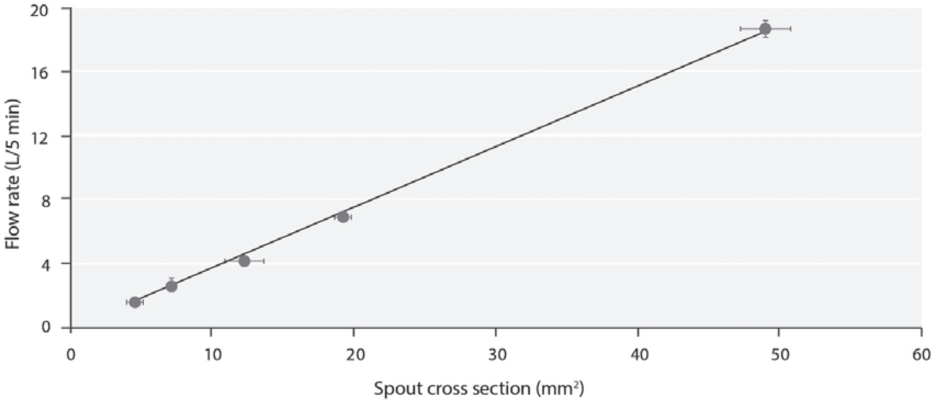

Figure 12 – Results from the testing of prototype tipping bucket nozzles.

have, with some confidence, been able to predict the performance of these types of extensive green roofs; however, the literature is lacking the same understanding with other locally sourced materials.

The data and findings from the GRIT Lab will ultimately enhance our understanding of these complex living architectures within the Toronto context. Since green roofs are now legislated in Toronto, it is important to evaluate the current construction practices to optimize the performance of green roofs.

The revised calibrations of the 5TE sensors have been in operation since August of 2013. These continue to accurately illustrate the differences in the water-retention characteristics of the two green roof planting substrate being tested. As part of a collaborative effort, the resulting analyses are being used to determine the available water for vegetation survival studies and the effect of antecedent conditions on stormwater management.

The tipping bucket gauges survived a less than -20°C (-4°F) winter with only one 3-D-printed nozzle delaminating due to ice clogging and expansion. The increased capacity provided by the new nozzles permits the laboratory to accurately record the response of the green roofs to a wider range of extreme rainfall events. This is extremely important for green roof research in the Toronto region in particular, where such summer events are anticipated to increase in the future.

By providing quantified metrics of the environmental performance for a diverse range of green roof construction and maintenance types, not only can we better predict these micro-site specific benefits, but these technologies can also have a greater effect on an urban scale. A fundamental aspect of this type of environmental research is ensuring that the sources of data acquisition are providing accurate findings, and with accurate findings comes confidence in performance predictability.

Building on these foundational stages in the research project, GRIT Lab researchers are currently preparing publications regarding annual water-retention statistics and green roof design, single-event hydrological characteristics, and aspects of winter hydrology in green roofs, including freeze/thaw cycling.

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