Leveraging Data for Green Infrastructure Performance Analysis and Prediction

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Abstract

In the twenty-first century, harnassing the power and abundance of environmental data has the potential to unleash a greater understand of and appreciation for the natural environment and enable better integration of the built environment by dynamically responding to the natural environment's processes. Reliably, accurately, and consistently collecting quality observations for monitoring, analysis, and future design adjustments becomes necessary when high volumes of data are able to be processed rapidly and automatically. In this thesis, I will demonstrate the need for, and benefits of, a data-oriented approach to Green Infrastructure design and analysis using the I-95 Revive project and PennDOT's SMP A site as a case study for robust monitoring networks capable of minute-by-minute measurements over a years-long span to enable better insight to the natural processes occuring in the rain garden and the potential effects on downstream hydraulics.

Acknowledgement

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Introduction

Modern cities are facing new and quickly emerging threats from increasingly frequent large storms, which wreak havoc on urban streams and tax urban drainage and sewer systems to dangerous levels.

Standardized Data Collection

This chapter will be based on my presentation given in April 2020 focusing on sensor network and flow measurement best practices.

Robust Data Storage

This chapter will be based on IDM paper and related work (R scripts, IDM formatter, etc...)

Performance Driven Data Analysis

4.1 Background

Green stormwater infrastructure (GSI) systems' performance has historically been difficult to measure. Most systems are designed and constructed using specifications drawn up over the last 25 or more years. While many states, including Pennsylvania, do require designs that take into consideration the pre-construction site conditions, or require a site to mimic the otherwise pre-anthropogenic environment's hydrology at the site, most do not include a post-construction monitoring plan, or predefined performance metrics that can be used to quantify a location's response to storm events over its lifespan. The lack of post-construction monitoring and analysis poses a major roadblock to improving recommendations for the design process that could lead to higher GSI longevity, lower the risk of GSI failure or under-performance, and creating uniform standards for GSI comparisons between geographically distinct sites or projects. Even when these monitoring requirements are in place, diverse site conditions, geographies, and climates necessitate a standardized framework for quantifying performance and comparing between potentially vastly different sites. This chapter outlines proposed key performance indicators (KPI) unique to infiltration-type rain garden GSI by looking at historical data for a site located in PennDOT's GR2 section of the I-95 Revive project (referred to as SMP A henceforth). These robust monitoring and analysis techniques will lead to consistent results that can be applied across many sites while ensuring that outside factors do not influence performance measurement results. A standard approach to analysis will open the door to suggested improvements for designs and further exploration of GSI's importance to more sustainable urban environments.

4.2 Recession Rate

Recession rate, or the change in depth of water ponded over time, is a potential key performance indicator (KPI) for GSI because it provides an easy to measure proxy for soil health. Soil health, in the context of GSI infiltration, is defined as a lack of compaction, clogging, or other infiltration inhibiting issues (Sokolovskaya et al., 2021). These properties of soil are heavily influenced by saturation level, which is a proxy for hydraulic conductivity and the shape and location of a soil-water characteristic curve (SWCC). Hydraulic conductivity of soil is the property that defines the ability of soil to pull water from the surface and through the soil column. The SWCC defines how a given soil responds to varying saturation levels, and the suction force applied to water in contact with the soil. Saturation of soil occurs when all the void space is filled with water and the movement of water through the soil column reverts to a gravity driven system that is largely influenced by soil characteristics. Saturated soil generally has the lowest hydraulic conductivity among the range of all volumetric water content (VWC) values possible for that given soil (Eyo et al., 2020). Different soils can have significantly different hydraulic conductivity ranges, and engineered soil with favorable properties (higher hydraulic conductivity) is generally specified for GSI design where infiltration is a desired treatment method.

By calculating a water level differential across consecutive data records, the change in water level can be used to determine periods of recession or intensifying ponding. When negative, recession is occurring, provided there in no rainfall or inflow currently happening. Additionally, the current water level must be confirmed below the overflow point of any outlet structures to ensure, as much as possible, that the recession rate can be attributed solely to infiltration. The magnitude of recession is important because it indicates the state of the GSI, or how saturated the soil is. Larger recession rates indicate a faster drawdown of the water level, while smaller values indicate potential saturation conditions. Comparing average recession rates calculated over the duration of a storm to other simultaneously recorded atmospheric and GSI state data shows the relationships that have the most significant impact on GSI performance. Changes in the recession rate over the period of a storm, or between the average recession of storms over a longer period of time, indicates changes in the soil health.

This relationship is complicated by several factors, namely the timing and size of an event, the state of the GSI at the beginning of an event from both a geomorphology and atmospheric scope, and the interaction between the two. The timing and size of a storm event, which can be best described by a combination of time of year, hyetograph, and the length of time since the last storm event, are important because these play the largest role in determining the pre-storm state of the GSI. The starting state, or condition, of the GSI is important because it necessitates an adaptable baseline against which analyze performance. For example, a storm taking place during early spring in the Philadelphia, PA region could have a wide range of pre-storm soil moisture, air and water temperatures, or plant growth conditions, to name a few. Additionally, the fact that suction head is highest when the soil is dry (Eyo et al., 2020), means that infiltration loss is greatest at the beginning of an event, no matter the specific initial conditions, because that is when the soil is driest. This confounding relationship means that the most consistent means of comparison will be between the most steady part of a storm event. For recession rates, this means looking at the trailing end of a storm, when there is no inflow, ponding level has reached its peak, and the soil has reached saturation. Allowing the GSI to reach a steady state means that comparisons will be made strictly between the soil's infiltration performance, without the influence of storm event timing characteristics.

The next section discusses the data used to support these hypotheses, and show that recession rate can be used as a proxy for soil health and extended to overall GSI performance. The data were collected with support from the Pennsylvania Department of Transportation (PennDOT) and AECOM as part of the I-95 Revive project. The site monitored is SMP A, a linear infiltration type GSI rain garden located on the southeast side of I-95 North between Frankford Avenue and Shackamaxom Street. The site includes two ponding and overflow locations (B1 and B2), three inlets piped from the adjacent raised highway bed, and two check dams splitting the garden into roughly equal thirds (upstream, gabion, downstream).

4.3 Data and Modeling

Data collected is 5 minute averages of 1 minute records (values are measured every minute and stored every 5 minutes as the average of the previous 5 values). This data resolution captures enough detail without producing an overwhelming number of data records. The following outlines relationships determined from data collected at SMP A over the course of nearly 3 years (May 2017 - November 2020), during which there were XYZ observed events with an average duration of PDQ [TODO: INSERT EVENT LENGTH HISTOGRAM]. [TODO: DISCUSS EVENT DATA DISTRIBUTION]

4.3.1 Temperature Dependence

The weather station at SMP A records air temperature, and each pressure transducer (PT) records the temperature of water in which it is submerged. The two types of temperature are highly correlated, and for the purpose of this analysis, only water temperature will be considered. Testing for variations in recession rate across the range of observed water temperatures shows a relationship that is largely linear (Figure 4.1).

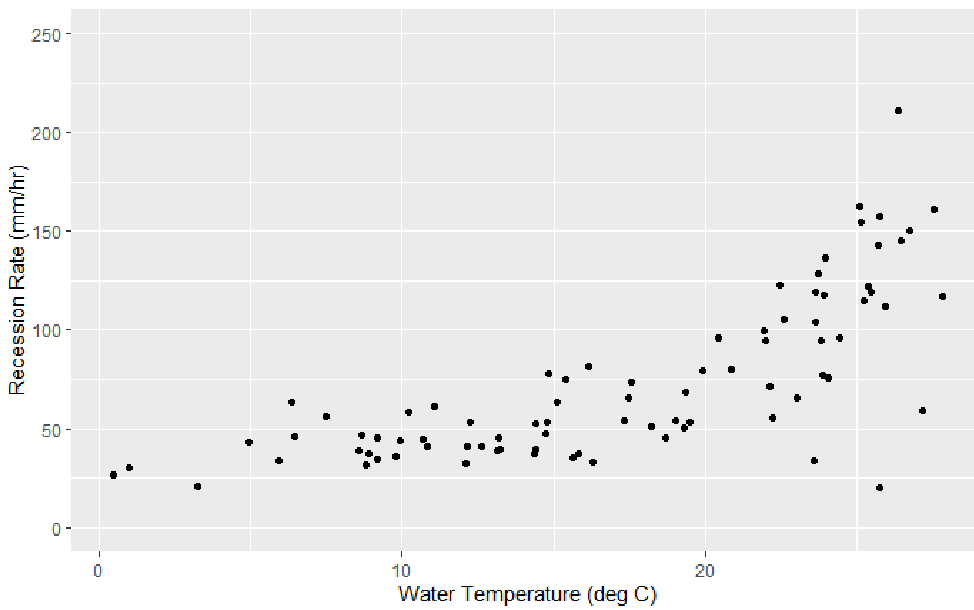

Figure 4.1: Average water temperature vs Recession Rate for SMP A storm event.

Calculating the average recession rate on a storm event basis and examining the distribution of these recession rates separated into bins (Figure 4.2) based on average water temperature shows a clear trend indicating higher recession rates at higher water temperatures. This aligns with several physical and hydrological models, namely that warmer water is less viscous and flows easier, especially through the soil (Emerson and Traver, 2008), and that since warmer soils contain warmer water, there is less internal resistance to flow by the soil at warmer temperatures. This means that GSI performance can be expected to increase during warmer months, both due to increased infiltration capacity and increased water uptake and evapotranspiration by the plant mass [CITE]. Furthermore, it has been shown that soils which have experienced multiple freeze-thaw cycles have higher values of saturated hydraulic conductivity due to the formation of internal ice crystal structures within frozen soils (Asare et al., 1999), which can expand pore space and increase the "development of macroscopic cracks and microscopic voids."

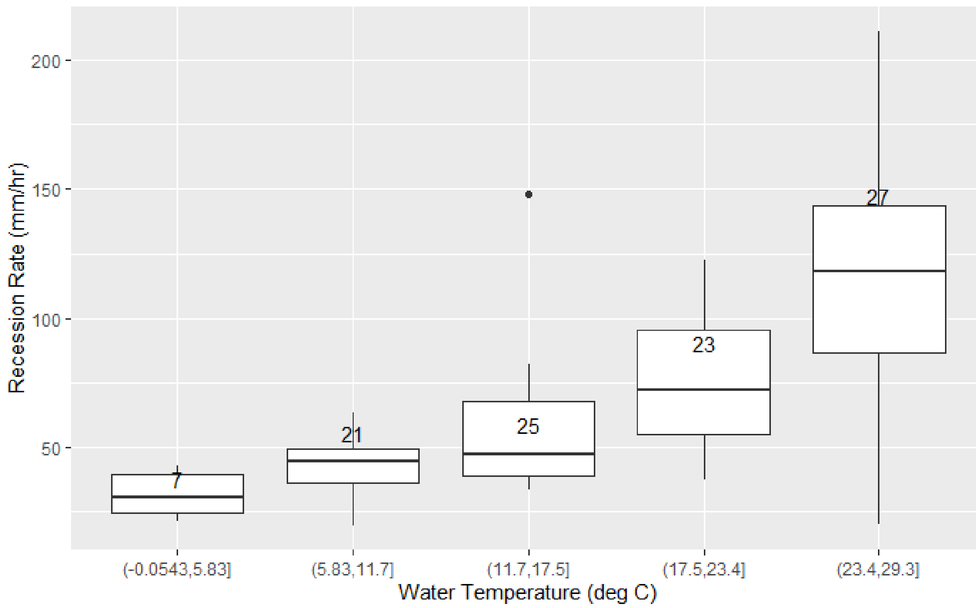

Figure 4.2: Average water temperature vs Recession Rate, separated into bins.

4.3.2 Atmospheric Influences

Both relative humidity (RH) and barometric pressure, both recorded in a similar fashion to air temperature at SMP A, showed no significant relationship with recession rate [TODO: INSERT CHARTS]. Comparing the average recession rate to RH bins and pressure bins, similar to the approach taken in the previous temperature analysis, shows no correlation between different values for these variables as compared to the average recession rate. This means that GSI performance is not dependent on these atmospheric variables, which largely only impact the soil-air interface. The lack of relationship between the atmosphere and sub-surface infiltration mechanics is expected, since the soil contains enough mass to prevent significant influence from the relatively fast-changing atmosphere.

4.3.3 Ponding Depth Influence

The amount of water collected in the rain garden appears to similarly have no effect on the rate of recession. This runs contrary to expectations that greater head pressure at the soil-ponding interface would lead to higher recession rates. The rate of recession is consistent across nearly the entire ponding depth range. This could be due to the fact that sufficient sub-surface hydrostatic pressure exists such that it cancels out the head pressure seen at typical ponding depths of up to a maximum of less than 1 meter.

[TODO: check interaction effects in linear regression model for all aforementioned conclusions]

4.3.4 Comparisons to Julian Day

Another explanation of the variability in recession rate is the more simple Julian day approach. This suggests a seasonal variation to GSI performance that is largely independent of temperature, despite temperature being strongly correlated. To investigate this, a seasonal trend must be fit the to the data and subtracted away in order to determine if the adjusted recession rates remain as variable as the non-adjusted data.

4.4 Results and Discussion

Conclusion

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