Evaluation of the effectiveness of green infrastructure for stormwater management in urban Buffalo, NY

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PUSH Buffalo rain garden on Plymouth Avenue, Buffalo, NY.
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Abstract

The city of Buffalo, like many cities along the Great Lakes, relies on a combined sewer network, which joins sewage effluent and stormwater. When the system is overwhelmed, excess water is discharged from outfall locations into local freshwater basins. To reduce unwanted discharge the City and community partners have invested in establishing rain gardens, to mitigate the stormwater volumes that enter the combined sewer network.

Rain gardens offer a natural and aesthetically appealing space for surface runoff to enter, prior to runoff into the sewer network. Within the garden boundaries, the water may evapotranspire, naturally recharge into the groundwater, or pond on the surface. Using numerical modeling it is possible to quantify the benefits of these systems. The water balance is solved utilizes input parameters such as soil moisture and soil type using forward and inverse modeling approaches.

This research highlights the applicability of modeling water movement through rain gardens in order to optimize stormwater storage. Additionally, different soil type specific parameters were passed through these models to indicate the influence of excess surface water entering gardens via surface runoff. HYDRUS-1D is less equipped for additional large volumes of water, which suggests a combination of groundwater and surface water models might be beneficial for future research efforts.

Three Summary Points of Interest

● Representative variably saturated flow models are a viable method to effectively quantify a rain garden water balance.
● Inverse modeling can be utilized to capture the variability in rain garden moisture across one growing season.
● Model improvements might entail right sizing of rain gardens, and investigation of the impact from surface runoff via impervious surfaces.

Keywords

Green infrastructure, rain gardens, stormwater management, surface runoff, evapotranspiration, groundwater recharge, Buffalo NY
1. Introduction

For rust belt cities such as Buffalo, NY (Schilling and Logan, 2008), efficient control of stormwater volumes is imperative to maintain sewer system efficiency. Rust belt cities often have an abundance of aging grey infrastructure and impervious surfaces (Figure 1.1), which include deteriorating and cracked pipes. Buffalo and many other rust belt cities have combined sewer systems in which stormwater and sewage commingle within the same system. Therefore, large storm events might trigger combined sewer overflow (CSO) events, which is when stormwater overwhelms existing constraints of the combined sewer network (Karpf and Krebs, 2011).

Stakeholders and citizens of the city of Buffalo must combat the impact of these CSO events on local freshwater lakes and rivers, as there are numerous CSO points spanning the Buffalo Sewer Authority (BSA) sewershed (Figure 1.2). Additionally, it takes merely 0.12” of rain to trigger CSO events in Buffalo, which sends the stormwater sewage effluent into freshwater basins (Martin, 2014). One novel way to mitigate quantities of stormwater entering sewer systems is green infrastructure (GI), such as rain gardens, rain barrels, bioswales, bioretention cells, and green roofs. These GI are designed to capture stormwater, and create pathways for natural evapotranspiration (ET), short term storage, and groundwater recharge.

Throughout the past decade, both PUSH Buffalo, and the BSA have made tremendous progress and advances in the quantity, and types of green infrastructure (GI) installed across Buffalo. The BSA created the Rain Check 1.0 and 2.0 programs as organized efforts to mitigate the frequency and quantity of CSO events. Upon completion, the BSA is aiming for 1,315 acres of green infrastructure to be dispersed throughout Buffalo. Additionally, the programs implemented numerous rain gardens, stormwater planters and bioswales during phase one installations (Rain Check 2.0 Opportunity Report, Buffalo Sewer Authority).

Rain gardens (Figure 1.3) have the most flexibility in terms of their applicability across urban and suburban settings. Therefore, this study focused solely on rain gardens provided by PUSH Buffalo and BSA.
All rain gardens used for this report are located within the West side of Buffalo, proximal to several CSO outfalls that discharge into the Niagara River (Figure 1.2). The BSA rain gardens used for this research were recently constructed along Niagara St, and form a corridor to promote network based drainage (Rain Check 2.0 Opportunity Report, Buffalo Sewer Authority).

While the BSA rain gardens (Table 1) along the Niagara St corridor were constructed within the past year, the age of the PUSH Buffalo gardens ranges from 7-10 years. The heterogeneity in age between gardens offered an opportunity to explore how sedimentation, establishment of vegetation, and effectiveness of the gardens might change over time. An added benefit of incorporating gardens from each stakeholder was that each stakeholder used different methods and materials during garden construction.

The major difference between stakeholders is their aim and purpose for the rain gardens. PUSH Buffalo incorporates rain gardens within their sustainable housing projects. Therefore, these gardens differ from the BSA in that stormwater is captured from roofs, driveways, parking lots, and sidewalks, then is directed towards the garden. Alternatively, the BSA gardens used in this research form a “corridor” along Niagara Street. The purpose of the corridor is to capture the water from the street and adjacent sidewalks. The intent is when an upgradient garden is inundated with excess water, the runoff will continue down the corridor and enter the next garden.

High variability between sites called for multiple methods to analyze field data and constrain results. Many previous green infrastructure studies employ watershed scale or surface water numerical models to represent field conditions. However, the bulk of results for this research were processed using HYDRUS-1D (Šimůnek et al 2013), which is a numerical model that processes variably saturated flow within the unsaturated zone.

The HYDRUS-1D model was selected for this research due to its ability to solve Richards equation (Richards, 1931), while accounting for the soil properties which change based on soil moisture (van Genuchten, 1980). Additionally, one can utilize HYDRUS-1D to process both forward and inverse numerical models. Forward models take a variety of known or assumed inputs, and pass these data through the model, “forward” in time to a representative solution. Alternatively, inverse models use known field observations (i.e. soil moisture) as targets, and the modeler then adjusts soil properties to represent field conditions. Essentially, the input of inverse model parameters are altered during calibration until there is an adequate fit between the simulated data and field observations. One may then test the calibration through validation, where the same input parameters are passed through a different dataset, and the simulated data is again compared with the observed (Šimůnek et al., 2012).

In addition to forward and inverse model capability, HYDRUS-1D was chosen as a suitable model for its thoroughness at the point scale (Nichols, 2018).
The research presented here aimed to evaluate site to site variability. Therefore, it was assumed catchment scale models would be unable to account for the fine scale differences between sites. HYDRUS-1D outputs the water balance components that impact the unsaturated zone, which is an effective means for comparison between model runs and rain garden designs.

2. Methods

The bulk of field data were constrained via the conductance of double ring infiltration tests (Figure 2.1). Double ring infiltration tests are employed to calculate the infiltration rate of a specific point, depending on infiltrometer size. The rate that water passes through the inner ring yields the infiltration rate. Therefore, one must time the experiment, and monitor the volume of water that passes through the inner ring from start to finish.

In addition to the TDR data, precipitation data were obtained from a site 5 specific weather station, also contributed by the USGS. These precipitation data were utilized along with meteorological data provided by the Buffalo NY Mesonet station (NYS Mesonet, Station ID: BUFF). These transient NYS Mesonet data included; solar or net radiation [MJ/m²/d], maximum and minimum temperature [°C], relative humidity [%], and wind [km/day] (Šimůnek et al., 2013). Each of these data types served as inputs to either the forward or inverse models used for this research. These data spanned from May 21st-September 30th, 2020 for the inverse calibration, and March 1st-October 31st, 2019 for the forward model runs.

Each forward and inverse model outputs the complete water balance (eqs. 1) upon completion of each simulation, which was the main result of interest for all model runs. Water balance gains were attributed to precipitation and positive changes in storage, and water balance losses were due to Evapotranspiration (ET), groundwater recharge, surface runoff and negative changes in storage.

\[ \Delta S = (+) \text{ Precipitation} (-) \text{ Evapotranspiration} \]  
\[ \text{(-)Recharge} \text{ (-) Surface Runoff} \]  

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Inverse models were evaluated based on the fit between simulated and observed data, and the root mean squared error (RMSE). The RMSE is quantified to reveal the degree of error between the simulated and observed data.

3. Results & Discussion

The results presented here are a sampling of highlights from the overall research effort (Milleville, 2021). These results include double ring infiltrometer experiments to quantify infiltration rates, and model analysis with HYDRUS-1D. Each of these results had unique benefits and limitations, which will be discussed throughout this section.

3.1 Double Ring Infiltrometer Test Results

Double ring infiltrometer experiments experienced variability across each respective site (Table 3.1). The PUSH Buffalo sites (sites 1-4) had the greatest variability in comparison to the BSA gardens (site 5). Additionally, sites 3 and 4 experienced the maximum average infiltration rates across all gardens, with a moderate degree of standard deviation. These findings are fascinating in that although the gardens at site 5 were constructed within the sampling year, the PUSH Buffalo gardens that were 5-10 years old saw higher average infiltration rates.

<table>
<thead>
<tr>
<th>Site</th>
<th>Avg. Rate (L/min)</th>
<th>Min. Rate (L/min)</th>
<th>Max. Rate (L/min)</th>
<th>S Dev. Rate (L/min)</th>
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<td>0.005</td>
<td>0.560</td>
<td>0.143</td>
</tr>
<tr>
<td>2</td>
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<td>0.014</td>
<td>0.717</td>
<td>0.210</td>
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<td>0.332</td>
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<td>0.338</td>
</tr>
<tr>
<td>4</td>
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<td>0.115</td>
<td>1.680</td>
<td>0.415</td>
</tr>
<tr>
<td>5</td>
<td>0.437</td>
<td>0.076</td>
<td>1.560</td>
<td>0.447</td>
</tr>
</tbody>
</table>

Table 3.1 Double ring infiltration test results for each site. The average, minimum and maximum rates were included for each site, in addition to the standard deviation of the infiltration rate data for each site.

The reasons for a lesser average infiltration rate for the BSA gardens was likely attributed to the highest standard deviation, and range between minimum and maximum infiltration rate between all sites. Additionally, the BSA gardens were watered more frequently throughout the sampling summer, which in turn would have created increased antecedent moisture levels relative to the PUSH Buffalo sites.

The controls on infiltration rate are assumed to be connected to the sediment type, stratification, and antecedent moisture levels specific to each site. For example, the soil found at sites 3 and 4 had noticeable pebbles and deep rooting structures throughout the upper fill of the garden. Sites 1 and 2 had no presence of pebbles within the garden fill. Alternatively, garden 1 had a layer of compacted sand in the upper 10 cm that was analogous to a sandstone. Site 5 at Niagara St had a mulchy, fairly coarse fill that experienced maximum infiltration during drought like conditions. However, when increased antecedent moisture was present after watering events, the garden experienced noticeably less infiltration capacity. These results are only useful to a certain extent, as each sampling location only represents individual points within each respective garden. Results might be improved by performance of more infiltration tests, and a detailed analysis of the soil grain sizes and types found at each garden.

3.2 Inverse Modeling with TDR Probe Observations

The HYDRUS-1D inverse models used during this research were calibrated using field observations of TDR data at depths of 10, 30 and 60 cm during the Buffalo growing season (Figures 3.2 and 3.3). These field observations were plotted versus the simulated model data, which were calculated based on alterations to the soil hydraulic parameters. Bounds were placed on a range of soil hydraulic parameters to ease and expedite the iterative process for each model run.
Subsequent model runs were analyzed based on the fit between simulated and observed data, in addition to the root mean squared error from each model run (RMSE). The fit between these data at the 10 cm probe position was rather strong, given the oscillation of soil moisture near the surface (Figure 3.2). The precipitation events also line up quite well and just slightly ahead of the shifts in soil moisture, as anticipated. The simulated TDR data nearly covered the full amplitude during intense precipitation events when there were spikes in soil moisture, and the RMSE for the 10 cm probe was 0.0353, or 3.5%.

The fit between the simulated and observed data for the 30 cm probe was also quite strong, with an RMSE of 0.0233, or 2.3%. The 30 cm simulated data didn’t have quite the same coverage in TDR amplitude compared to the observed data, however the fit during moderate rain events was rather exceptional. One probable reason for the improvements at the 30 cm depth is that there were less fluctuations in soil moisture compared to those experienced by the 10 cm probe near the soil surface.

One unique field condition that impacted both the 10 and 30 cm probe models (Figures 3.2 and 3.3), is that there were multiple periods where the BSA had to water the gardens throughout the growing season. The impact of watering exposed the TDR probes to shifts in soil moisture that were in turn unaccounted for within the precipitation data.

Additionally, one must ensure that the TDR probes are properly instrumented in the horizontal direction to receive accurate readings. There are extensive influences on the error associated with numerical models, which means it is vital to exercise caution while instrumenting and preparing field data.

3.3 Influence of Impervious Surfaces on Surface Runoff and Model Efficacy

One field condition that was unaccounted for in many of the representative and inverse models was the impact of additional runoff from impervious surfaces with sizeable footprints (Figure 3.3).

![Figure 3.3 Plotting of impervious capture zones (CZ) in Google Earth, to account for additional surface runoff that enters the gardens and the respective models. The footprints for each CZ were 128.9 m² for CZ1, 177.8 m² for CZ2, 123.9 m² for CZ 3, and 134.3 m² for CZ 4.](image-url)
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Evaluation of this effect was performed by utilization of Google Earth to delineate capture zones (CZ) of impervious street surfaces and estimate approximate rain garden areas. These CZs were aligned in the upgradient direction of overland flow down the Niagara St corridor, and digitized to encapsulate all street surface runoff that might impact a specific garden. Due to old Google Earth aerial imagery, rain garden dimensions were approximated with the help of field photographs.

Models associated with these CZs were processed using different soil hydraulic parameters as inputs, specifically; for inverse calibrated, sand, and silt loam soil types (Figures 3.4-3.6). The inverse model soil hydraulic parameters (Figure 3.4) were calibrated using the TDR probe observations, and represent the closest proxy to field conditions. The sand and silt loam soil hydraulic parameters were based on default parameters within HYDRUS-1D [Simůnek et al., 2013]. The precipitation and meteorological growing season data from 5/21/20-9/30/20 were held constant, however these precipitation values were multiplied to account for each additional square meter of runoff from the CZs.

Capture zones (Figure 3.3) were all similar in spatial extent, as CZ 1 was 128.9 m$^2$, CZ 2 was 177.8 m$^2$, CZ 3 was 123.9 m$^2$, and CZ 4 was 134.3 m$^2$. These values serve as a valuable reference while interpreting the following results, as each HYDRUS-1D model is assumed to represent one square meter of rain garden area. Meanwhile, rain garden areas at each CZ were estimated at 15 m$^2$ for CZ 1, 9 m$^2$ for CZ 2, 11 m$^2$ for CZ 3, and 13 m$^2$ for CZ 4, for an average of 12 m$^2$. This average of 12 m$^2$ is assumed for the following discussion, because only a portion of these results applies to the inverse calibrated Niagara St parameters.

The average Niagara St rain garden area of 12 m$^2$ was then divided by each CZ area, to provide an estimation of the contributing area of CZ to rain garden unit area (m$^2$). These calculations were once again averaged due to the similar dimensions between gardens, which led to an approximate value of 11.75 m$^2$. Essentially, this 11.75 m$^2$ value represents the amount of additional capture zone runoff that each square meter of rain garden is responsible for infiltrating. The x-axis of the following plots (Figures 3.4-3.6) denotes each added square meter of CZ runoff. Therefore, the “goal” for each garden model is to attain and surpass the 11.75 m$^2$ threshold on the x-axis. Any additional area beyond 11.75 m$^2$ would suggest that the sediment type within the model is capable of processing water volumes greater than that provided by the 2020 growing season.

![Figure 3.4 Plotting of the water balance percentages for the parameters calibrated within the inverse model. This model represents the as constructed rain gardens on Niagara St. Evapotranspiration denoted by green, recharge by orange, runoff by red, and change in storage by purple.](image-url)

The soil hydraulic parameters calibrated by the inverse model were processed first, based on their representation of true field conditions on Niagara St (Figure 3.4). After incorporating three square meters of additional CZ contributing area, potential ET had a noticeable decline with a simultaneous increase in groundwater recharge and gain in storage. There were no signs of surface runoff. Models did not converge beyond a 12 m$^2$ addition of CZ area; however, by this point nearly 100% of water within the model was considered groundwater recharge (Figure 3.4). These data suggest that the Niagara St gardens were a near perfect fit for the additional CZ contributions from the 2020 growing season. Although the models did not converge beyond 12 m$^2$, it is promising that gardens showed zero surface runoff across all model runs, which implies they were sized appropriately.

Alternatively, the model runs with sand as the input for the soil hydraulic parameters were capable of running up to 80 m$^2$ of extra CZ contributing area (Figure 3.5). The first 12 m$^2$ displayed very similar trends to that of the inverse model multipliers for each water balance component (Figure 3.4). Again, this suggests that sand filled gardens would effectively
manage stormwater volumes comparable to the 2020 growing season. However, once 25 m$^2$ of CZ area was introduced to the model, there was a spike in surface runoff, a decline in groundwater recharge, and approximately zero ET (Figure 3.5). This trend continued towards the addition of 80 m$^2$ of CZ area, where over 30% of the water balance consisted of excess runoff ponding on the surface. These results are still promising, in that runoff was not present until the threshold of 11.75 m$^2$ for CZ contributions was more than doubled (25 m$^2$). Even so, runoff only contributed to roughly 5% of the water balance at 25 m$^2$.

Notable shifts in water balance components were observed under the use of silt loam hydraulic parameters (Figure 3.6). There was an immediate jump in surface runoff to about 50% of the water balance after an addition of 3-5 m$^2$ of CZ area. Furthermore, after incorporating an extra 10 m$^2$ of CZ area surface runoff dictated over 70% of the water balance (Figure 3.6). With 10 m$^2$ being just below the contributing CZ area goal of 11.75 m$^2$, one must conclude that 100% silt loam soil fills would be disadvantageous to rain garden performance. Additionally, models did not converge beyond a CZ addition of 100 m$^2$, at which nearly the entirety of the water balance was considered surface runoff.

Figure 3.5 Plotting of the water balance percentages for default sand parameters within HYDRUS-1D [Šimůnek et al., 2013]. Evapotranspiration denoted by green, recharge by orange, runoff by red, and change in storage by purple.

These model results are useful in that they represent the impact that impervious surfaces have on rain gardens, which was one of the main goals of this research. These data suggest that both the in-situ, calibrated soil conditions at Niagara St are well suited to enhance rain garden efficiency, which highlights the work done by the BSA. The other results indicate that the default soil hydraulic parameters for sand are well optimized for rain garden performance, while the silt loam models performed poorly, with high percentages of surface runoff.

However, these results hinged upon the assumption that water is capable of fully infiltrating laterally throughout the garden. More specifically, that the approximated CZ areas were equally distributed across the entirety of each approximated rain garden area. Henceforth, we assumed that all water entering the curb cut inflows made equal contributions to each square meter within the garden area. Execution of this outcome is possible in the field; however, field conditions must be well constrained. Ideally, the entire garden extent would be positioned beneath street grade to promote horizontal flow paths. Alternatively, one could implement a sort of shallow drainage pipe that is pitched to disperse water to the garden end opposite of the inflow.

While these results are promising, they also emphasize the benefit for further assessment of the influence of surface water during numerical modeling of green infrastructure. Numerical models that place equal emphasis on groundwater and surface water flow could fully encapsulate the dynamics of a rain garden.
Additionally, different assumptions and field experimentation methods could further advance the understanding of the interaction between impervious surfaces and rain gardens throughout Buffalo.

4. Policy Implications

Green Infrastructure can be expensive to build and maintain. However, there are also expenses in following a business as usual approach and continuing to allow storm water to trigger combined overflow events. These combined overflow events cause economic damage in the form of closed breaches and federal fines as a result of uncontrolled releases of pollution into waterways. As a result, the City of Buffalo and community partners have taken the initiative to implement a green infrastructure approach to reduce uncontrolled discharge of pollutants during high precipitation events.

The work presented here is a first step in efforts to quantify the efficacy of these rain gardens in slowing down and in some cases holding storm water in an effort to reduce the number of combined sewer overflow events. Through the modeling framework it is possible to help optimize the construction of these rain gardens with respect to the types and layer thickness of soils needed to maximize water storage and potentially reduce construction and maintenance costs. This analysis can be done for current and future climates (Milleville, 2021).

5. Outreach Comments

To our knowledge this is the first numerically modeling-based study of the green infrastructure systems in the City of Buffalo. Working with our partners, our goal is to help quantify the benefits of rain gardens in the city of Buffalo. Not all community members appreciate the installation of rain gardens as they can be sinks for garbage coming off the streets as well as sources of weeds if not properly maintained. Through the work presented here we are focused on helping community members understand the water quantity and quality benefits of rain gardens and help change public opinion for those who may not see the benefits of these systems.

6. Student Training

This grant supported the training of one Masters’ student at the University at Buffalo. In addition the field sites developed during this grant were also used for experiential learning opportunities for the 2021 UB undergraduate Field Camp program (GLY 407) and graduate level Field Methods in Hydrogeology (GLY 563) course.

Figure 6.1. Infiltration test conducted at the School 77, Plymouth Avenue rain garden by the 2021 Field Methods in Hydrogeology class.

Publications/Presentations


Acknowledgements

Thank you to the Buffalo Sewer Authority and PUSH Buffalo for providing the access to rain gardens utilized throughout this research. Also, thank you to the Buffalo Niagara Waterkeepers and the Erie County Water Quality Committee for showing interest in this research. All of your support drove the motivation for this research, and will hopefully advance the study and design of the rain gardens and green infrastructure in Buffalo.

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