Case Study

Green Infrastructure in Series Reduces Thermal Impacts of Stormwater Runoff

Charitha Gunawardana, S.M.ASCE[1]; Matthew Dupasquier[2]; and Walter McDonald, A.M.ASCE[3]

Abstract: Stream temperatures across the world are increasing due to changes in land use and climate, especially in urban areas. This leads to hydrologic urban heat islands, where higher water body temperatures can have negative consequences on ecological and human health. Green infrastructure is a potential solution to mitigate the temperature of urban runoff; however, it is unclear how green infrastructure systems, especially those connected in series, can be best utilized to reduce the impact of urban runoff on downstream temperatures. This study seeks to fill this gap by monitoring a green infrastructure system in Milwaukee, WI—a bioswale and permeable paver that both discharge into a second bioswale—to evaluate its temperature mitigation potential. Results indicate that for the bioswale and permeable pavers connected in parallel, the bioswale outperformed the permeable pavers in reducing event mean temperatures (2.8°C cooler). In addition, the bioswale that performed secondary treatment further reduced the average event mean temperature across all storms by 4.2°C from the permeable pavers and 2.4°C from the bioswale. This study demonstrates the effectiveness of a green infrastructure connected in series in reducing runoff temperatures, which is important for addressing a critical threat to environmental and human health. **DOI: 10.1061/JSWBAY.SWENG-486.** © *2023 American Society of Civil Engineers.*

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Introduction

Temperatures in streams and rivers are increasing across the world, especially in streams that are impacted by urbanization (Kaushal et al. 2010). While climate change plays a major role, this is exacerbated by anthropogenic land cover, such as impervious surfaces, that have a greater thermal capacity than natural land covers and a direct hydrologic connection to surface water bodies. These impervious surfaces capture solar radiation and transfer that energy to stormwater runoff and subsequent downstream water bodies (Herb et al. 2008; Zeiger and Hubbart 2015). This creates hydrologic urban heat islands, where urban streams have comparatively higher baseflow temperatures and are subject to greater temperature surges from stormwater runoff (Zahn et al. 2021). Coupled with rising global air temperatures (Pachauri and Reisinger 2007) and uncertainty in the hydrologic cycle (Huntington 2006), this is likely to influence ecological processes and community shifts in freshwater bodies (Nelson and Palmer 2007). This includes negative impacts to temperature-sensitive species (Caissie 2006), increased contaminant toxicity (Patra et al. 2015), and proliferation of toxic algal blooms (Griffith and Gobler 2020). It is therefore imperative that stormwater is managed in a way that mitigates the temperature of stormwater runoff to protect human and environmental health.

One potential management approach to increasing urban runoff temperatures is green stormwater infrastructure that captures, treats, and infiltrates stormwater runoff at the source. Green stormwater infrastructure has been shown to be an effective approach to manage stormwater volumes and pollutants in urban and agricultural settings (Clary et al. 2020; Regier and McDonald 2022). In addition, it has been demonstrated as an effective means of reducing the urban heat island effect through lower ambient air temperatures (Balany et al. 2020). It can also reduce runoff temperatures through heat exchange that occurs when runoff filters through cooler green infrastructure plants and media. Temperature itself is also an important component to the hydraulic performance of green infrastructure as temperature of stormwater runoff entering a green infrastructure practice influences the infiltration rate due to temperature-dependent changes in viscosity (Emerson and Traver 2009; Lewellyn et al. 2016). However, despite the potential for green infrastructure to reduce runoff temperatures and its importance in their overall performance, the impact of specific green stormwater infrastructure types on temperature mitigation of urban stormwater runoff is underexplored.

One type of green stormwater infrastructure that has potential to reduce the temperature of stormwater runoff is permeable pavements. These systems, which capture stormwater runoff through gaps on the surface and then filter and infiltrate through a trench filled with crushed aggregate, are effective at reducing stormwater runoff volumes and reducing pollutant concentrations (Sambito et al. 2021). Permeable pavements may mitigate runoff temperatures by redirecting stormwater through cooler permeable pavement media and soils. Permeable pavements built out of concrete or brick pavers have been shown to have lower surface temperatures than other permeable surfaces such as porous asphalt (Cheng et al. 2019); however, the comparative surface temperatures of permeable to impermeable pavements are unclear, with studies finding permeable pavements to be both lower (Cheng et al. 2019) and higher (LeBleu et al. 2019)

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than impermeable surfaces. This divergence could be due to variations in surface roughness or heat capture within saturated pore spaces that influence temperatures of these surfaces.

Bioretention practices are perhaps the most studied green stormwater infrastructure practice for thermal mitigation; however, the most appropriate way to use them to meet downstream temperature goals is unclear. Bioretention practices have produced statistically significant reductions in both peak and mean temperatures during simulated rainfall events for watersheds that contain streams with temperature-sensitive trout species (Long and Dymond 2014). Design components that influence temperature reductions in bioretention include the soil depth of effluent pipes, as well as the size of the contributing watershed area (Jones and Hunt 2009). However, bioretention alone may not be enough to reduce runoff temperatures to levels needed for temperature-sensitive species (Chen et al. 2021; Ketabchy et al. 2019), where, at a watershed scale, it has been correlated to higher downstream water temperatures (Jalali and Rabotyagov 2020).

One potential solution is connecting green infrastructure in series in a treatment train that can effectively reduce pollutants to acceptable levels. A connected green infrastructure in series has been shown to improve volume-based reduction goals (Wadzuk et al. 2017; Woznicki et al. 2018), and improve the removal of pollutants from stormwater runoff (Brodeur-Doucet et al. 2021; Winston et al. 2020). However, the impact of green infrastructure connected in series for reducing thermal pollution in urban stormwater runoff is underexplored. While research has demonstrated the cumulative effect of rain gardens and riparian buffers on receiving stream temperatures (Martin et al. 2021), studies evaluating the impact of green infrastructure directly connected in series are lacking. Therefore, more research is needed to determine comparative thermal mitigation among practices, the appropriate design of those individual practices for optimizing temperature reductions, and the best placement and configuration for achieving watershed-level outcomes (Martin et al. 2021; Timm et al. 2020).

The overarching goal of this study is to monitor the hydrologic and temperature mitigation of three green infrastructure practices that are hydraulically connected to determine their utility for runoff temperature reduction. To do so, we (1) monitored the effluent of three stormwater management practices (a permeable paver system and two bioswales) for temperature and flow rate over a 4-month period; and (2) analyzed the data to determine reductions in peak temperature and event mean temperature throughout the system. Findings have implications for the development of temperature mitigation strategies using green stormwater infrastructure as both a standalone practice and installed in series, to address a critical threat to human and ecological health of urban water bodies.

Materials and Methods

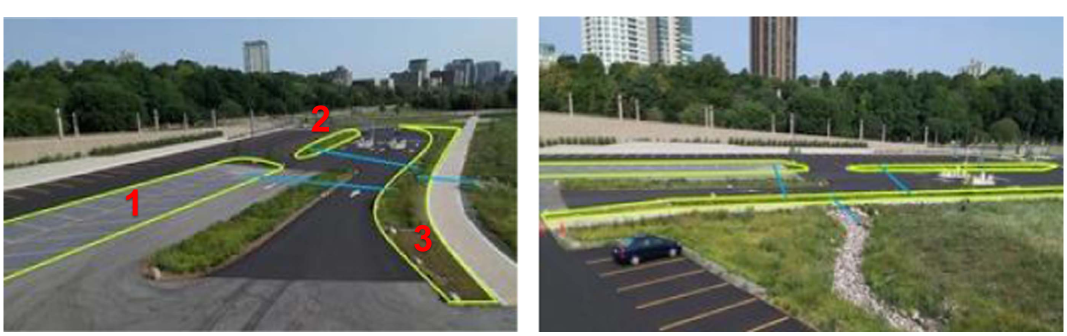
Site Description

The Milwaukee War Memorial parking lot was constructed in the spring of 2021 and has a surface composed of a mix of asphalt and permeable pavement surfaced with concrete pavers. The runoff from the parking lot is managed using a combination of bioswales and permeable paver systems that discharge at various points into a rip-rap lined swale. For this project, the outlets of three green infrastructure practices were monitored for flow and temperature including: (1) a permeable paver system collecting parking lot runoff, (2) a bioswale collecting parking lot runoff, and (3) a downstream bioswale that collects parking lot runoff and runoff from the underdrain of 1 and 2, and then discharges to a rip-rap lined swale (Fig. 1).

- The permeable paver system is approximately 465 m^2 in size and collects runoff from an overall area of 1,580 m^2. The paver system is unlined and is drained by a 6-in. (0.15 m) diameter, 35.7-m long perforated PVC pipe (0.001% slope) and is then discharged through a 6-in. (0.15 m) diameter, 20.1-m long PVC underdrain (1.5% slope) that outfalls to the surface of Bioswale 2.
- Bioswale 1 has an area that is approximately 222 m^2 and drains a total area of 2,062 m^2. It is planted with a mix of native grasses and shrubs. It is unlined and has a 6-in. (0.15 m) perforated PVC pipe runs underneath the bioswale for 40.2 m (0.001% slope) and connects to an 8-in. (0.20 m) overflow grate where effluent is ultimately discharged through a 6-in. (0.15 m) diameter, 19-m long (0.5% slope) underdrain that outfalls to the surface of Bioswale 2.
- Bioswale 2 is approximately 270 m^2 and collects runoff from the underdrain of the permeable paver system, Bioswale 1, as well as a drainage area of 1,775 m^2. The bioswale is planted with a mix of native grasses and shrubs. It is unlined and has a 6-in. (0.15 m) perforated PVC pipe that runs 63.7 m along the bioswale (0.5% slope). This underdrain is connected to an 8-in. (0.20 m) overflow pipe, and effluent is discharged through an 8-in. (0.20 m) diameter, 17.5-m long underdrain (0.5% slope) that outfalls to a rip-rap lined swale.

Monitoring Methods and Equipment

To continuously measure water level and temperature, Onset HOBO U20 water level sensors were placed within the outlet of each structure and a v-notch weir was placed at the end of each outlet pipe to estimate flow rates. The water level sensors collected



(a) (b)

Fig. 1. Photo of green infrastructure facing north, with monitored infrastructure outlined in bright green (1: permeable pavers; 2: bioswale 1; 3: bioswale 2) and connectivity of the underdrains in blue (a); and photo of green infrastructure facing west, along with a gravel rip rap channel that the system discharges into (b). (Images by Matthew Dupasquier.)

(a) (b)

Fig. 2. Bioswale 2 outfall into rip-rap channel, rain gauge, and data logger (a); and data logger in Bioswale 2 that measures the discharge from the permeable paver and Bioswale 1 underdrains (b). (Images by Matthew Dupasquier.)

both water level and temperature at 2-min intervals over the study period. Additionally, an Onset HOBO tipping bucket rain gauge was installed at the site to collect rainfall data that was applied to estimate overland flow volumes into the green infrastructure practices. All sensors were connected to one of two data collection hubs that were solar powered and broadcasted data through a cellular connection (Fig. 2).

Volumetric Flow Computations

Influent runoff into each green infrastructure practice entered as overland flow; therefore, influent flow rates were estimated using rainfall data collected at the site. The rainfall data was applied to the rational method for estimating peak flow and volumes into the green infrastructure practices

$$Q = ciA \tag{1}$$

where Q is the flow volume; c is the runoff coefficient; i is the rainfall depth over the specified time period; and A is the drainage area. The catchments of each practice contained asphalt parking lots and therefore a runoff coefficient of 0.9 was used. Flow in the effluent of the underdrains was calculated using a standard equation for a 90-degree v-notch weir

$$Q = 2.49h^{2.48} \tag{2}$$

where h is the height of the water behind the weir as measured by the water level sensors.

Temperature Computation

The temperature at each outlet location was evaluated using both the peak temperature observed during a storm event, as well as the event mean temperatures (EMTs) (Picksley and Deletic 1999). The event mean temperature represents a volume-weighted average of the temperature in the runoff during a storm event and is represented by the following equation:

$$EMT = (\Sigma(V_i * T_i))/(\Sigma(V_i)) \tag{3}$$

where V_i and T_i are the runoff volume and temperature at time step i. To determine the influence that ambient air temperature and solar radiation had on the effluent temperatures in the green infrastructure, linear regression was performed to estimate the EMT computed above with air temperature and solar radiation as the independent variables.

In addition to peak temperature and EMT, the slopes of the increase and the decay in temperature were evaluated using the following equation for each rain event:

$$T = \beta_0 + \ln(t) * \beta_1 \tag{4}$$

where T is the temperature; t is the time after the start of the event (mins); and β_0 and β_1 are regression coefficients. Regression coefficient β_1 represents the slope of the increase or decay, and was determined for each individual runoff event. Summary statistics were calculated for all observed events. The runoff events were delineated based upon rainfall that was separated by at least 24 h.

Results and Discussion

Hydrological Performance

A total of 21 runoff events were captured at the site over a period from June 29, 2021 to October 29, 2021. During these events, the three green infrastructure practices were estimated to reduce 91% of the stormwater runoff volume on average as indicated in Fig. 3. The volume reduction through individual structures was similar in magnitude, with the permeable pavers, bioswale 1, and bioswale 2

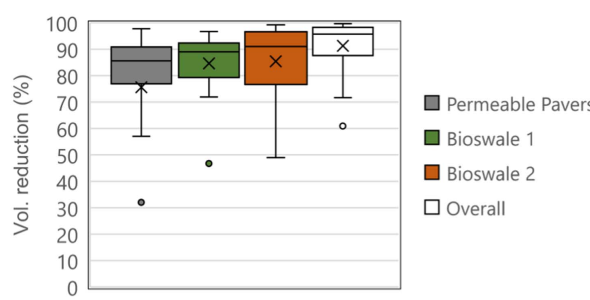


Fig. 3. Distribution of the percent of stormwater runoff volume per rain event that is reduced by the three green infrastructure practices and the overall system.

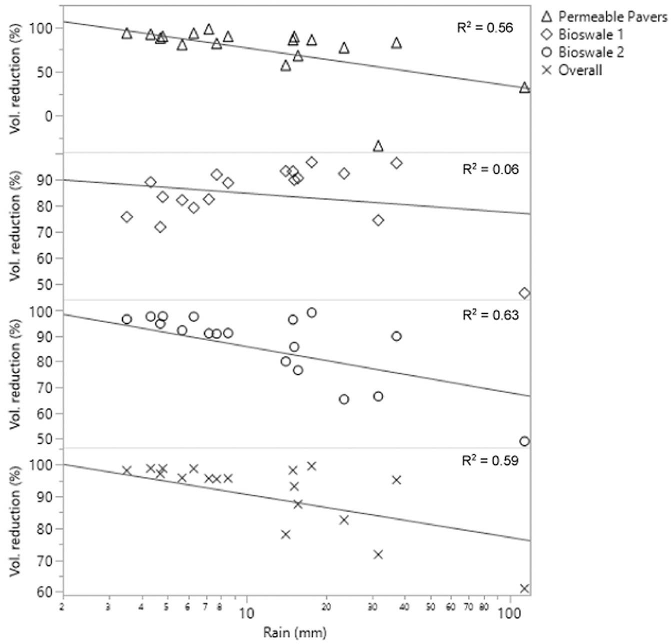


Fig. 4. Percent of stormwater runoff that is infiltrated as a function of rainfall depth.

producing average volume reductions of 77%, 84%, and 85%, respectively. The observed higher overall volume reduction (91%) is due to the placement of the green infrastructure in series, where the overflow of the permeable pavers and bioswale 1 is further reduced through bioswale 2.

To evaluate how volume removal was influenced by storm characteristics, we plotted the volume reduction percent as a function of the log of the rainfall depth (Fig. 4). As illustrated, the permeable pavers, bioswale 2, and the overall system had a statistically significant relationship ($p < 0.05$ of the slope coefficient) between the percent of the volume captured and the rainfall depth, suggesting that the volume reduction capacity of the green stormwater infrastructure decreases as it becomes more saturated during larger rainfall events. However, the impact of rainfall depth on volume reduction for bioswale 1 was less clear.

Overall, the green infrastructure system reduced peak flow rates by over 98% on average, with slightly less reduction in the permeable pavers (90%) than the bioswales (both 95%) (Fig. 5). Similar to volumetric performance, the peak flow reductions were impacted by the size of the rainfall event with less peak flow reduction for

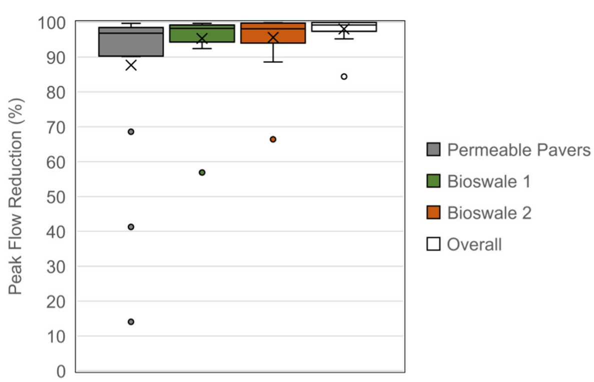


Fig. 5. Distribution of the peak flow reduction in each green infrastructure practice and the overall system.

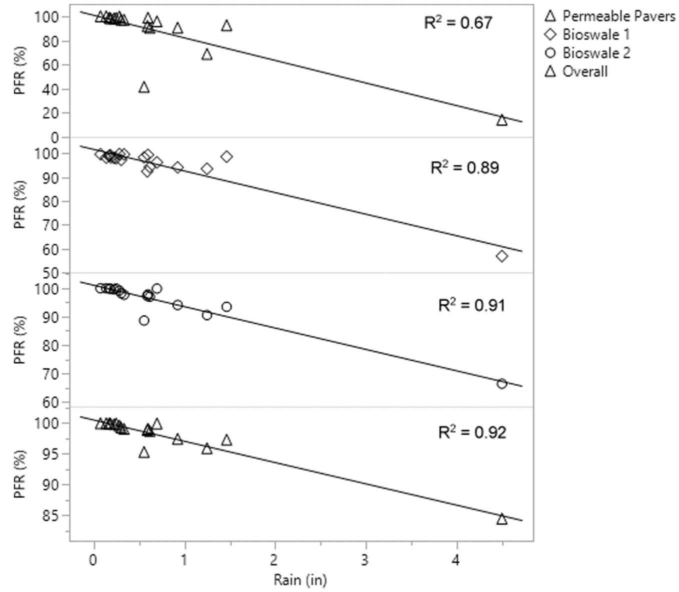


Fig. 6. Peak flow reduction (PFR) as a function of the rainfall depth.

larger rainfall events (Fig. 6). While there is an observable outlier at the far end for a storm with greater than 100 mm depth, it does not have significant influence on the liner regression model with a Cook's D value less than 1.0 for all models (Helsel et al. 2020).

Temperature Performance

For the two green infrastructure practices in parallel—permeable paver and bioswale 1—the bioswale had both a lower peak temperature and EMT across all storms (Fig. 7). Further EMT reductions were observed in Bioswale 2, which on average was 4.2°C cooler than the permeable pavers and 2.4°C cooler than the Bioswale 1. This is within the range of other studies that have found median temperature differences between the influent and effluent of green infrastructure between 0.8°C and 8.8°C (Jones and Hunt 2009; Long and Dymond 2014). The reduction in EMT was similar in magnitude for the peak temperature with the Bioswale 2 on average 4.3°C cooler than the permeable pavers and 3.4°C cooler than Bioswale 1. On an ANOVA test, the peak temperature for Bioswale 2 was significantly ($p < 0.05$) lower than the infrastructure feeding into it while permeable paver had a significantly higher EMT than the bioswales. The reductions in both EMT and peak temperatures highlights the potential for green infrastructure in series as a way to further mitigate runoff temperatures. In fact, by treating the stormwater runoff further, this system reduced the EMT to 22°C on average, below the upper temperature tolerated by trout for 1–14 days of 22.5°C in the upper Midwest of the US. (Wehrly et al. 2007).

To evaluate the impact that ambient air temperature has on the peak and event mean temperature, we plotted all outflow water temperatures as a function of the date of the runoff event and colored by ambient air temperature (Fig. 8). In this figure, the peak and event mean temperature points are fit with spline interpolation to illustrate the trends over time. As illustrated, the air temperature is cooler towards the beginning and end of the study period and appears to peak during August. Not surprisingly, this appears to have a substantial impact on the peak and event mean water temperature, as these follow a similar trend. During these events at the height of the summer, the temperature of the water leaving Bioswale 2 is above the threshold for freshwater species of 22.5°C (as indicated by the horizontal line), suggesting that despite further reductions in

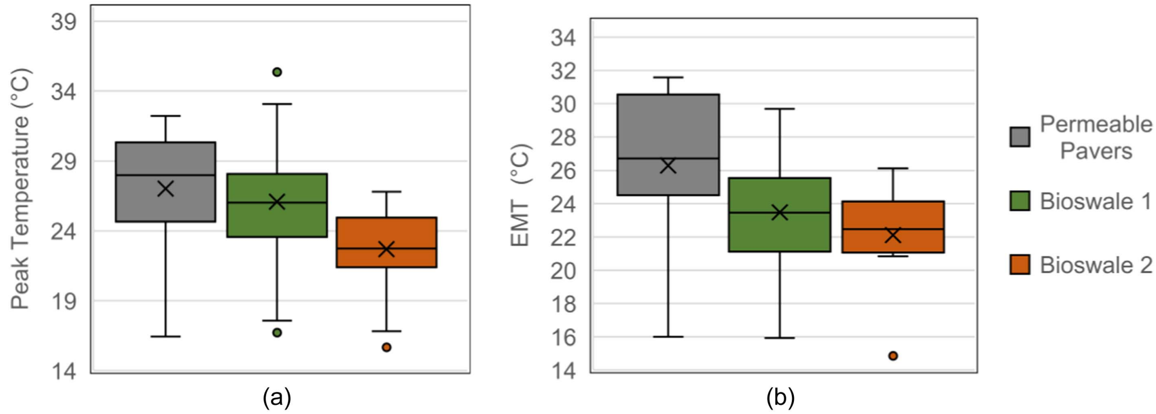


Fig. 7. Distribution of the peak temperature (a) and the event mean temperature; and (b) for stormwater runoff events captured at the underdrain of each green infrastructure practice.

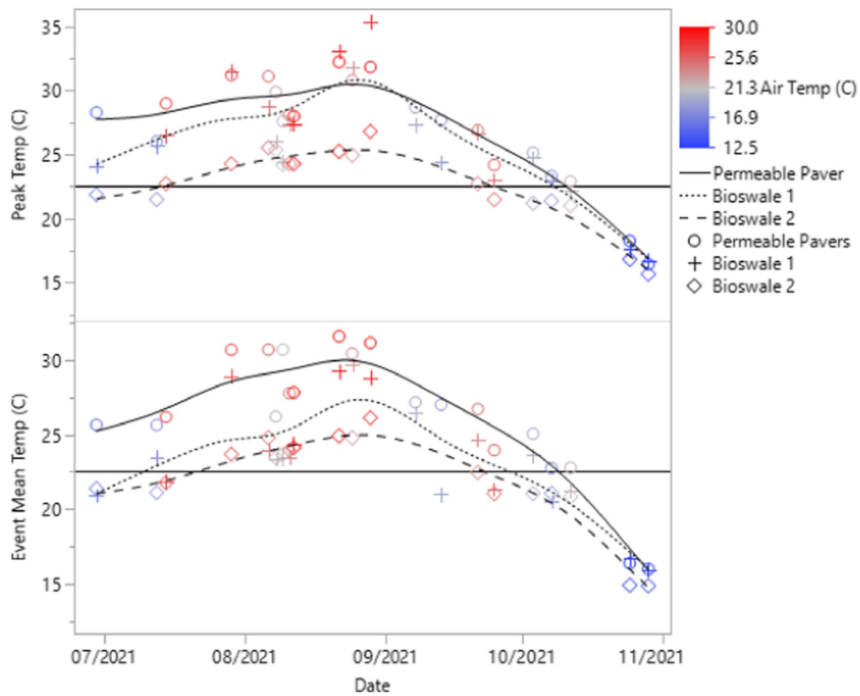


Fig. 8. Peak temperature and event mean temperature as a function of the date. The ambient air temperature for each event is represented by the color bar and the horizontal line represents the minimum mean temperature threshold for freshwater species (22.5°C).

temperature, the green infrastructure in series may not be enough to meet that threshold.

To further understand the impact of ambient conditions, we evaluated the correlation between air temperature and solar radiation immediately preceding the storm event on the EMT and peak temperatures of the green infrastructure system using linear regression. The relationship between air temperature and solar radiation on the EMT of each structure is illustrated in Fig. 9. As illustrated, there is a positive correlation between both air temperature and solar radiation, with periods of zero solar radiation during nighttime storms. This may indicate that when both the ambient air is warmer and incident solar radiation is higher, the runoff into the green infrastructure is hotter due to higher warming of the pavers within the catchment of each practice.

An example of the change in temperature over the course of a runoff event is illustrated in Fig. 10 for a storm on August 21, 2021. During this runoff event, temperatures at the outlets initially decrease, likely due to the flushing of cooler water from the green infrastructure (within the underdrain pipe or subsurface of the green infrastructure itself) than the ambient air temperature or temperature of the standing water behind each weir. However, after the initial decrease, the temperature immediately spikes. This is particularly pronounced for Bioswale 1 and the permeable pavers that collect direct surface runoff from the asphalt parking lot. Additionally, the falling limb of the temperature appears to vary among the bioswales and permeable pavers with Bioswale 1 having a sharp drop in temperature while the permeable pavers and Bioswale 2 had a more gradual reduction.

To further evaluate the temporal dynamics of effluent temperature during runoff events, we quantified the rate of change in the rising and falling slopes of the temperature. This rate of change is represented as β_1 from Eq. (4) and the distributions of β_1 across all

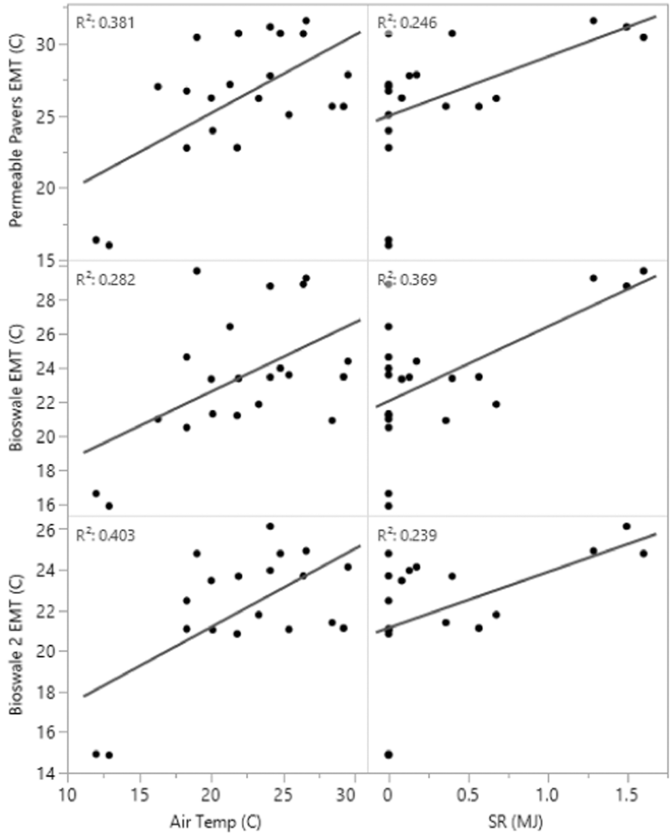


Fig. 9. Relationship between EMT and air temperature and solar radiation (SR).

observed storms is illustrated in Fig. 11. As illustrated, the permeable paver has the slowest rate of increase in comparison to the bioswales, with Bioswale 1 having the greatest rate of increase overall; however, none of these were statistically different using the students t-test ($p < 0.05$). In evaluating the rate of decay, the permeable paver and Bioswale 2 had a similar decay; however, Bioswale 1 had a significantly steeper decay ($p < 0.05$) than the other green infrastructure practices. This could be due to several factors. In comparison to the permeable pavers, Bioswale 1 could have a greater cooling capacity than permeable pavers, which is also evident in the lower peak and event mean temperatures. For Bioswale 2, it could be that it is receiving effluent from the other bioswale and permeable pavers; therefore, there is a lower rate of heat exchange due to the lower temperature of influent. Other possible mechanisms driving these differences are discussed in the following section.

Implication of Results

The green infrastructure connected in series reduced both the EMT and peak temperatures, on average, to levels that are below the threshold for freshwater fish species in the Midwest United States of 22.5°C (Wehrly et al. 2007); however, this was not the case in the hottest summer month, as the EMT and peak temperatures were strongly influenced by ambient temperatures. The bioretention installed in parallel to the permeable pavers had lower event mean and peak temperatures, and had a significantly higher rate of temperature decay. This could be due to several factors including an increased residence time within the bioswale to facilitate energy transfer, cooler soil and plant temperatures on the surface of the bioswale than the surface of the permeable pavers, or temperature and thermal conductivity differences between soil media in the bioretention and crushed aggregate media in the permeable pavers. Bioretention, consisting of soils and plants, is known to have a lower surface temperature than permeable pavers, which could be a factor in its performance. This is largely due to the thermal conductivity of the material, as well as other factors such as shading from plants within the bioretention itself (Muerdter et al. 2018). In addition, the primary mechanism for which runoff temperatures are reduced is heat dissipation through conduction with the media

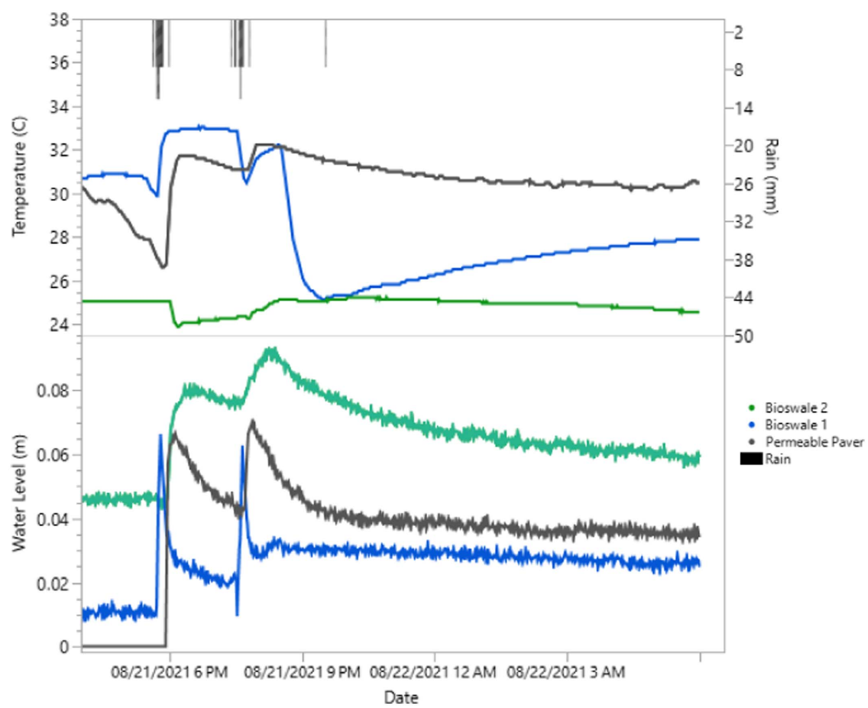


Fig. 10. Example of temperature fluctuations over the course of a runoff event.

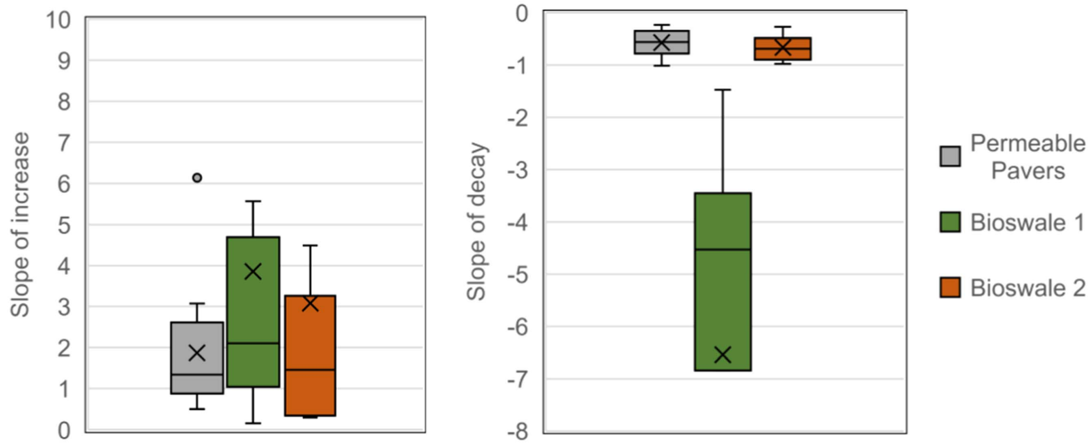


Fig. 11. Slope coefficients of the increase and decay of the effluent temperatures.

when runoff is filtered through the green infrastructure practice (Chen et al. 2021; Long and Dymond 2014). While not quantified in this study, the thermal capacity of the media may be something that plays a considerable role in temperature mitigation as soils generally have a greater thermal capacity than permeable pavers. In addition to reductions of event mean and peak temperature, the significant overall volume reduction (91%) further reduces the impact of elevated stormwater runoff temperatures on downstream waters. This indicates that volume reduction through capture, infiltration, and evapotranspiration, in as much as temperature reduction, is an important component to consider for thermal mitigation.

While the results demonstrate the overall outcome of green infrastructure in series, there are several limitations to the monitoring approach that limit the interpretation of the data. Because the runoff entered the system as overland flow, there is no data on the temperature of the runoff as it enters the green infrastructure practices. While this does not significantly affect the comparative analysis between practices, it does limit our understanding of the overall reduction in runoff temperatures, especially in the green infrastructure practices in the headwater. An inability to directly measure overland flow also means that there may be uncertainties in the computation of incoming peak flows and volumes using a modeling approach based upon rainfall data. Additionally, there could be uncertainties within the estimations of effluent flow rates using a water level and weir. Based upon this data, we are also unable to define the extent to which thermal cooling of the stormwater runoff occurs within different portions of the system. For example, cooling could occur in the bioretention as it infiltrates through the soil layers, as well as during its transport through the underdrain.

To that end, the outcomes of this work lead to several potential research directions that would be valuable for elucidating the exact design characteristics of green infrastructure for mitigating runoff temperature. First, the specific thermal capacity of the media for effectively reducing runoff temperatures is something that is underexplored and may have competing objectives with the need to adsorb pollutants and infiltrate runoff at a sufficient rate. For example, sand is known to have a greater thermal capacity than clay soils (Ghuman and Lal 1985); therefore, the recommended mix of bioretention media may be an important consideration. There may also be design parameters for the depth of the underdrain that could impact the temperature of the effluent that leaves the system, with greater depths to underdrains producing lower effluent temperatures due to the cooler temperature of deeper soils that are buffered from atmospheric temperatures changes and solar radiation (Jones and Hunt 2009). Even so, there may be design and cost considerations that limit the depth to which the underdrain can be installed.

Conclusions

This study evaluated the impact of green stormwater infrastructure connected in series on the temperature mitigation of stormwater runoff. Results indicated that for the bioswale and the permeable pavers connected in parallel, the bioswale outperformed the permeable pavers in event mean temperature reduction (2.8°C cooler); however, neither was able to decrease the event mean temperature below the 22°C threshold for freshwater trout species. The bioswale that performed secondary treatment did, however, further reduce the temperature of the cumulative effluent across all storms, as the average event mean temperature of Bioswale 2 was 4.2°C cooler than the permeable paver and 2.4°C cooler than the bioswale 1. These findings have practical implications as increasing global temperatures and land development will further the impact of stormwater runoff on stream temperatures. Therefore, for stormwater managers, the need to reduce the thermal load of stormwater runoff will likely only grow as temperature becomes a driver of water body impairments. This study demonstrates that green infrastructure can be a useful tool in the mitigation of runoff temperatures, especially those installed in series.

Data Availability Statement

All data, models, and code that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

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Supplemental Materials

Tables S1 and S2 are available online in the ASCE Library (www.ascelibrary.org).

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