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Evaluating the influence of design strategies and meteorological factors on tree transpiration in bioretention suspended pavement practices

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Abstract

Impervious surfaces, such as roads, parking areas, and buildings, found in cities throughout the world have significant impacts on urban hydrology due to increased volumes and peak flow rates of run-off delivered to receiving waterbodies. Bioretention practices are a common stormwater control measure used to mitigate the impacts of urban run-off. When coupled with suspended pavement systems, which provide tree roots with an uncompacted soil matrix that enhances root access to oxygen and water, engineers can design subsurface alternatives to manage urban stormwater. Two suspended pavement systems designed to function as subsurface bioretention practices were installed on the campus of the University of Tennessee, Knoxville, Tennessee, USA. Sap flow sensors using the heat ratio method were installed in two bald cypress (*Taxodium distichum*) trees to characterize the role of transpiration in the suspended pavement systems. Mean transpiration rates were greater when water availability was higher in the bioretention media. Regression models indicated that atmospheric vapour pressure deficit (kPa) was the most influential environmental parameter on tree transpiration and that stomatal regulation of water losses was evident when water was limiting. Findings from this study illustrate how tree transpiration rates can vary, even between individual trees of the same species, on the basis of conditions within the practice, and provide insight to practitioners on how design parameters influence fine-scale tree–water relations in bioretention systems to maximize the contributions of transpiration on system hydrology.

KEYWORDS

bioretention, green infrastructure, sap flow sensors, suspended pavement systems, transpiration, urban trees

1 | INTRODUCTION

The prevalence of urbanization and the subsequent increases in stormwater run-off production have led to the deterioration of urban streams and receiving water bodies throughout the world (Walsh, Fletcher, & Ladson, 2005). With the evolution and enforcement of stormwater discharge-related regulations, cities and municipalities are implementing stormwater control measures as cost-effective, green infrastructure style approaches to refine their stormwater management programmes (United States Environmental Protection Agency, 2009). An example of a type of green infrastructure implemented to manage urban stormwater is bioretention practices, one of the most popular and widely used stormwater control measures in the United States and throughout the world (Davis, Hunt, Traver, & Clar, 2009). Bioretention practices typically consist of an excavated area of land backfilled with an engineered sandy soil media topped with mulch and various types of vegetation, though numerous design variations have been implemented in practice (Davis, 2008). In addition to improving water quality through biogeochemical treatment processes, a key objective of bioretention practices is the reduction of run-off volumes and peak flow rates to more closely mimic predevelopment hydrology (Hunt, Davis, & Traver, 2012). Bioretention designs influence stormwater run-off hydrology by utilizing soil media with relatively high infiltration rates (standards vary by state) and including bowl volumes for additional surface storage prior to infiltration (Davis et al., 2009). Volume reduction is primarily achieved through two mechanisms. First, run-off that has infiltrated into the soil media can exfiltrate into surrounding in situ soils. Second, stormwater can be lost via soil evaporation and transpiration by vegetation, commonly combined as evapotranspiration (ET; Berland et al., 2017). Previous research has demonstrated that ET can serve an important role in managing the water budget of bioretention practices.

Several studies have characterized the role of ET in bioretention practices through a variety of methods. Li, Sharkey, Hunt, and Davis (2009) used a field-based water balance approach in a bioretention practice planted with unidentified trees and shrubs and lined with an impermeable membrane (to eliminate exfiltration) and found that losses due to ET accounted for 19% of run-off volume reduction. Winston, Dorsey, and Hunt (2016) used DRAINMOD to model ET from three low-permeability bioretention practices planted with a variety of plant types, including shrubs, sedges, native grasses, and trees, and reported that 4.5–5.5% of the water balance in each system could be attributed to ET. In a more controlled approach, Wadzuk, Hickman, and Traver (2015) used weighing lysimeters to compare ET in bioretention mesocosms planted with native grasses and found that 50% of direct rainfall was converted to ET in freely draining systems, whereas mesocosms with an internal water storage (IWS) layer converted 78% of direct rainfall to ET, though the authors indicate these figures represent a high estimate. Similarly, Denich and Bradford (2010) used weighing lysimeters to measure ET in a bioretention practice and reported average ET rates of 4.2 mm day^{-1} in sunny, dry summer weather.

Although these studies provide valuable insights on the overall water balance of bioretention practices, there is a relatively coarse understanding of ET and how it varies in these systems. Isolating transpiration from ET can provide critical information on temporal changes in this component of the water balance and ultimately improve plant selection and hydrological modelling for bioretention systems. Further, literature is limited on the potential role of trees in bioretention practices. As a long-lived plant type with significant above-ground and below-ground biomass, trees may improve the hydrological performance of bioretention practices (Scharenroch, Morgenroth, & Maule, 2016). In one of the few studies of tree transpiration in bioretention practices, Scharenroch et al. (2016) studied the impact of various tree species on the water balance of a parking lot outfitted with several green infrastructure practices. Using measurements of stomatal conductance to model monthly transpiration, transpiration from trees accounted for 46–72% of the total water outputs from the systems (Scharenroch et al., 2016). However, differences in the responses of individual trees (both within and between species) to storm events may not be evident at the monthly timescale, and changes in transpiration patterns in response to varying design configurations were not investigated.

To address these knowledge gaps, transpiration rates of bald cypress trees (*Taxodium distichum*) planted in two field-scale bioretention suspended pavement practices installed on the campus of the University of Tennessee (Knoxville, TN, USA) were studied using sap flow sensors. Sap flow sensors utilize high-resolution thermometric measurement techniques to relate the velocity of heat transfer through xylem tissue to tree water use (Burgess et al., 2001). Though measurements of sap flow have been widely implemented to characterize tree–water relations in forestry-related fields, no studies have conducted sap flow measurements in trees planted in bioretention practices to date. Average transpiration rates and the degree of influence of local meteorological conditions were compared between the two systems to evaluate the impact that bioretention function and differences in design parameters had on tree–water relations. The objective of this study was, for the first time, to utilize direct measurements of sap flow to quantify the impacts of hydrological regime and design parameters on tree function and water use in bioretention practices.

2 | MATERIALS AND METHODS

2.1 | Site description

The study was conducted on the campus of the University of Tennessee (Knoxville, Tennessee, USA, 35.9606°N, 83.9207°W, elevation approximately 270 m) between May and July 2017. The location is characterized by a temperate climate, with a mean annual temperature of 16°C and mean annual precipitation of 1,215 mm (Tennessee Climatological Service, 2018). Mean daily temperatures between May and July historically range from 19°C to 26°C in Knoxville, TN (National Weather Service, 2018). The study sites consisted of two suspended pavement systems that were installed in winter 2016. Suspended pavement systems are commercially available devices that transmit loads from paved surfaces to a compacted subsurface, creating a matrix of uncompacted soil media that promotes tree health by providing increased root access to air and water not commonly found in typical urban soils (Page, Winston, & Hunt, 2015). When backfilled with bioretention media, suspended pavement systems can become effective subsurface alternatives to traditional bioretention practices when space is limited, as is often the case in urban areas (Page et al., 2015). The two systems (hereafter referred to as the “north site” and “south site”) were constructed in a similar manner, where an area of land, sized appropriately to the contributing drainage area using the Natural Resources Conservation Service curve number method and a design storm size of 25.4 mm, was excavated, lined with a gravel subbase, and backfilled with bioretention media following the installation of the suspended pavement devices (U.S. Department of Agriculture, 1986). The same suspended pavement system product and bioretention media were used in both sites. The drainage areas for both systems were completely impervious, with both sites receiving run-off from different sections of a small two-lane road. In both systems, stormwater run-off derived from the contributing drainage area was routed towards the inlet, where a series of perforated pipes distributed the water underground across the top of the bioretention media to percolate through the profile and allow for treatment. Runoff that had moved through the bioretention media at the north site drained into the underlying native soils, whereas an underdrain system was installed at the south site to collect and transmit excess stormwater that had percolated through the media profile (and did not exfiltrate into the underlying soils) to a monitoring point located at the back of the practice. Both sites were fitted with overflow pipe networks that bypassed the practices during extreme rain events. Due to local constraints, the systems were topped with topsoil and planted with turf grass in place of pavement. Bald cypress (*T. distichum*) trees of approximately 5-cm diameter at breast height were planted in each system in March 2017. Root barrier devices were installed at both sites to direct the roots of the trees into the bioretention media. Due to its limited scope (i.e., only two unreplicated suspended pavement practices were studied), further research is needed to validate the results of this preliminary investigation into the performance of trees in suspended pavement systems, though findings from this work can provide some insights on the effect that design strategies have on tree performance in these practices. The cross-sectional components of the south suspended pavement system are shown in Figure 1. Additional information about the study sites is presented in Table 1.

2.2 | Meteorological and water-level measurements

Local climate data were collected at the study site using Campbell Scientific sensors taking temperature (T, °C), relative humidity, rainfall (P, mm), and total solar radiation (R_s, MJ m^{-2}) readings. Total solar radiation was assumed to be the equal at each site, though shading from adjacent vegetation may have caused potential differences in R_s. Weather data were recorded every minute and logged to a Campbell Scientific logger. The vapour pressure deficit (D, kPa) of the atmosphere was calculated using the ASCE Penman–Monteith method (Allen et al., 2005). Measurements of water depth in the suspended pavement systems relative to the bottom of the bioretention media were recorded every minute using UL-20 water-level loggers (Onset HOBO) positioned in screened, perforated well pipes that were installed in each practice during construction. Local climate and water-level data were collected for all 74 days of the study period.

TABLE 1 Description of bioretention suspended pavement systems

Parameter	North site	South site
Drainage area (m^2)	183.0	138.5
Surface area (m^2)	22.3	27.5
Drainage configuration	No underdrain	Underdrain
Drainage area imperviousness (%)	100	
Depth of gravel subbase (cm)	10.2	
Media composition	93% sand, 7% fines, and 5% OM by weight	
Media depth (cm)	71.1	

Note. OM: organic matter.

2.3 | Sap flow measurements

Sap flow measurements were performed using the heat ratio method via SFM1 sap flow meters (ICT International) installed in each tree approximately 0.5 m above the ground in mid-April 2017 (Burgess et al., 2001). The SFM1 sap flow sensors consist of a 35-mm central heating probe abutted by two 35-mm measurement probes, each containing two thermistors positioned 7.5 and 22 mm away from the tip of the probe to provide area-weighted measurements of sap flow radially across the sapwood. Measurements were conducted every 10 min

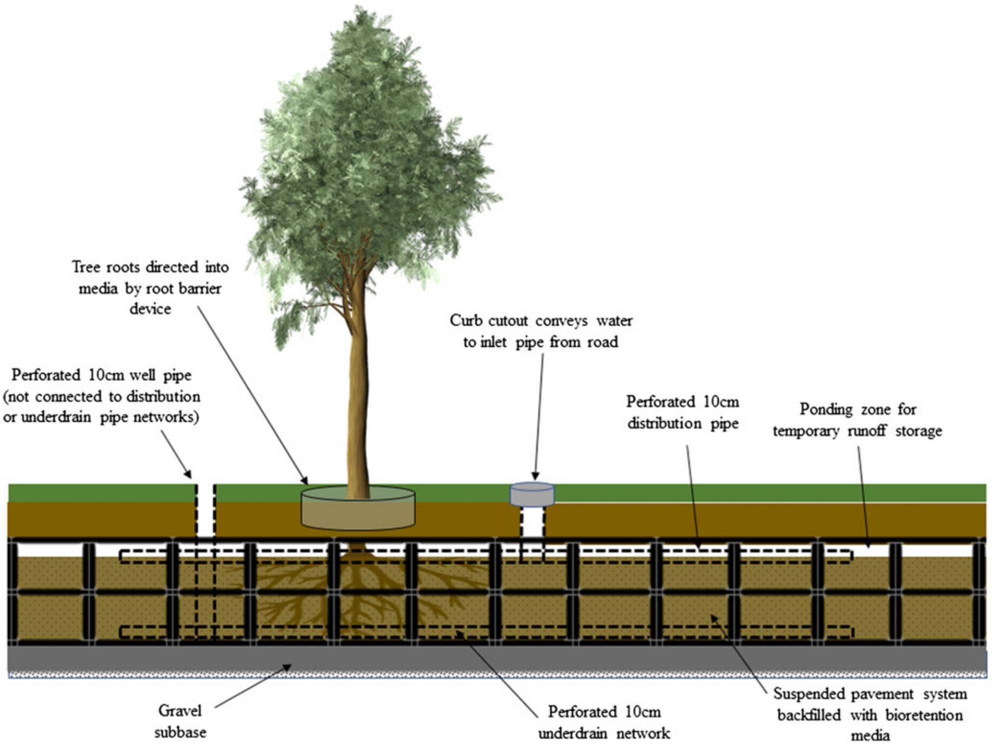

FIGURE 1 Cross section showing components of south suspended pavement system

by sending a pulse of heat from the central heating probe and recording the ratio of temperature increases at the upstream and downstream measurement probes over a fixed period. The rate at which this heat pulse travels up or down the stem can then be converted to sap flow using several equations and correction factors that account for wounding, probe misalignment, and water content of the sapwood. A more thorough explanation of measuring sap flow using the heat ratio method can be found in Burgess et al. (2001). Because this study focused on comparing relative changes in tree water use between the two suspended pavement systems and destructive calibration techniques required to characterize sap flow (kg hr^{-1}) were not possible due to ongoing research, heat pulse velocities (V_h, cm hr $^{-1}$) were used as a proxy for transpiration, and the mean of the daily minimum readings at each site were used as zero-offset values for sensor calibration (Burgess, 2006). Although measurements of V_h can provide qualitative insights on the patterns of tree water use, this approach cannot be used to directly quantify the amount of water used by trees. If quantifications of tree water use were desired, several calibration procedures and correction factors would be needed to transform readings of V_h in order to report rates of sap flow and tree water use. Due to the small diameter at breast height of the trees used in the study, the sapwood thickness was assumed to be equal to the diameter of the stem for both trees, similarly assumed in O'Brien, Oberbauer, and Clark (2004). Sap flow data collection began approximately 2 weeks after sensor installation to account for the formation of wounds in the sapwood around the probes. Sap flow data were successfully collected for the entire 74-day study period at the south site, whereas 67 days of data were available for the north site due to equipment failures associated with depleted batteries used in the field to power the sensors.

2.4 | Statistical analyses

Meteorological data were compiled into daily and hourly means (T and D) or daily and hourly totals (P and R_s), whereas hourly means were used for water-level and V_h readings. Inspections for normal distributions in the data were conducted using the Shapiro–Wilk test, which indicated that the water-level and heat pulse velocity data collected at both sites were not normally distributed. Correlation analyses using Spearman's ρ were performed to identify connections between meteorological factors and both water level and sap flow. Wilcoxon signed rank tests were performed to test significant differences in sap flow values between sites. Time series and multivariable linear regression analyses were conducted to model the influence of daily averaged meteorological parameters (P, T, D, and R_s) on transpiration. Results from the Ljung–Box test indicated that significant autocorrelation was present in all parameters excluding temperature, so lag_1 terms were added to the models to reflect the influence of sap flow and meteorological conditions from the previous day on measurements of a given day. Models were created using mixed-direction stepwise regression techniques. Normality of the residuals was confirmed using the Shapiro–Wilk test, whereas autocorrelation in model residuals was assessed using the Durbin–Watson test. All results were considered statistically significant at $p < 0.05$. Statistical analyses were performed using the statistical software packages JMP Pro 13.2 (JMP, 1989–2007) and R (R Core Team, 2016).

3 | RESULTS AND DISCUSSION

3.1 | Meteorological and water-level data

The meteorological data observed at the study site were characteristic of the typical transition between spring and summer in the Knoxville area (Figure 2). Rain of 234.3 mm occurring on 33 of the 74 days of the study period was recorded. The daily mean temperatures ranged from a low of 9°C to a high of 28°C, with a mean daily temperature of 22.3°C occurring during the study. The mean daily vapour pressure deficit was 0.83 kPa, and the daily total solar radiation fluctuated between 6.7 and 28.2 MJ m^{-2}. Water levels in the wells of both suspended pavement systems were significantly correlated with hourly rainfall, mean hourly D, and hourly total radiation readings ($p < 0.01$). The mean water level in the north site during the study was 15.5 cm, significantly higher than the mean south site water level of 8.2 cm ($p < 0.0001$, data not shown). Soil moisture sensors installed in each practice after the scope of this study support this trend, as mean soil water content was significantly higher in the north site than the south site ($p < 0.0001$, data not shown). This indicates significant differences in the availability of water in the bioretention media profile at both sites, with the north site retaining more water and maintaining a higher water level than the south site, which may not have provided the bald cypress tree as much access to water due to the lower mean water depth. Differences in water level may be attributable to the presence of the underdrain network (or lack thereof in the north site), which likely regulated water levels in the south site, as well as potential variations in the composition of the subsoils underlying each suspended pavement system.

3.2 | Sap flow

Transpiration rates exhibited clear diurnal trends throughout the study, with maximum values near midday and minimum values occurring overnight (Figure 3). Heat pulse velocities at both sites were positively correlated to hourly mean T, D, and R_s and negatively correlated to hourly P ($p < 0.0001$). The interactions between these climate factors and tree physiological processes help explain the daily behaviour of sap flow. Daily maximum sap flow values occurred during peak daily T, D, and R_s levels, as photosynthetic rates increased and water vapour concentration gradients between the leaf and the atmosphere reached peak values, followed by a decline in sap flow as these parameters decreased during night-time hours (Pallardy, 2008). We hypothesize that sap flow declined following rain events as inundated, oxygen-deficient soils inhibited root respiration rates (Pallardy, 2008). Once run-off passed through the upper soil layers, soils became reoxygenated, root respiration recovered, and subsequent increases in sap flow rates occurred (e.g., as recorded between Days 125–130 and Days 155–160; Figure 3). An example of how water level and heat pulse velocities were influenced by a rainfall event is shown in greater detail in Figure 4.

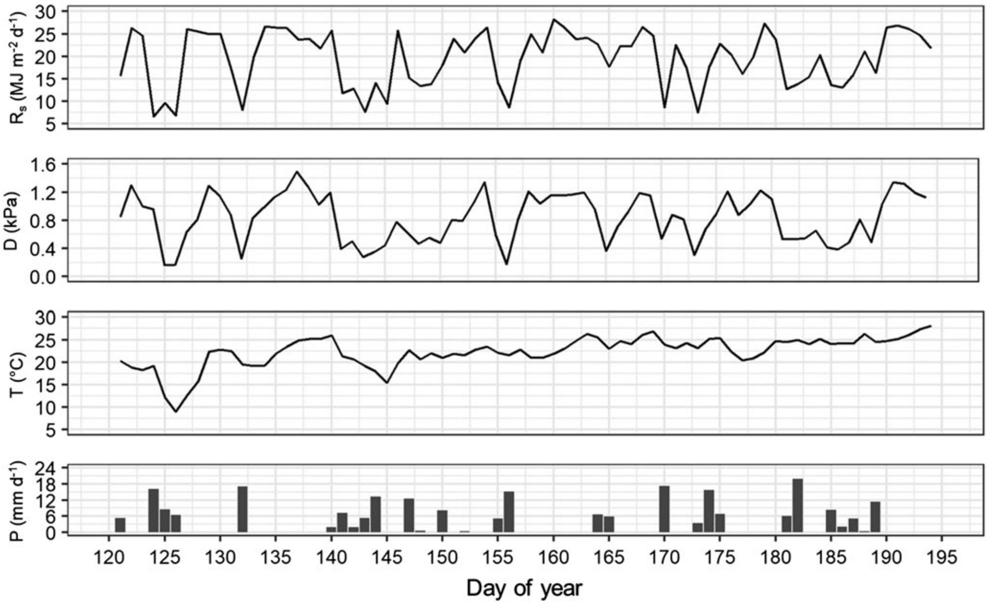

FIGURE 2 Trends of daily total solar radiation (R_s, MJ m^{-2}), mean daily vapour pressure deficit (D, kPa), mean daily air temperature (T, °C), and total daily rainfall (P, mm) observed at suspended pavement sites during study

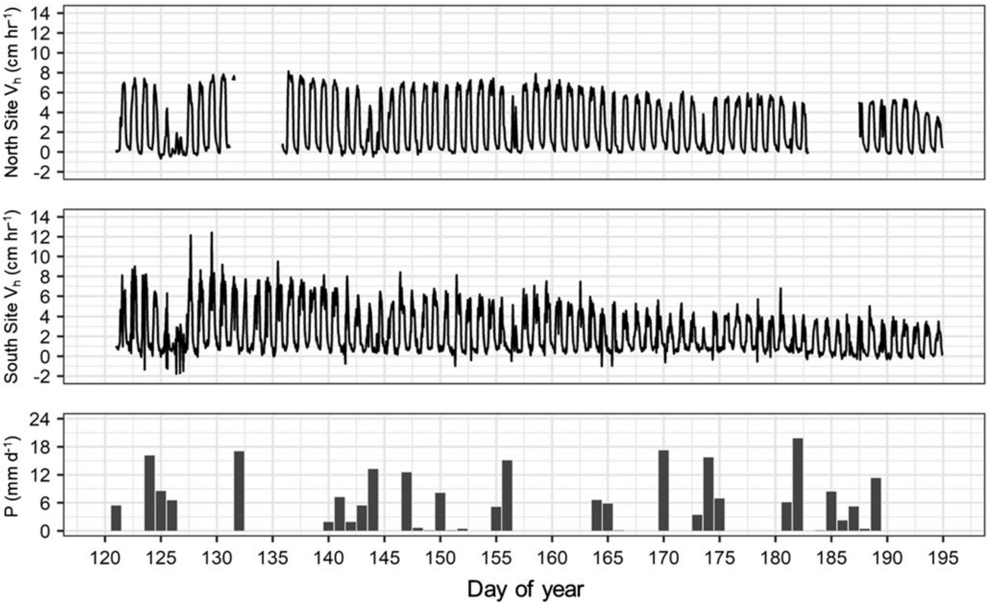

FIGURE 3 Diurnal trends of mean hourly heat pulse velocity (cm hr^{-1}) and daily rainfall totals (mm day^{-1}) recorded during the study. Missing heat pulse velocities at the north site occurred due to equipment power failure

The mean hourly heat pulse velocity at the north site (2.65 cm hr^{-1}) was significantly higher than the mean value recorded at the south site (2.38 cm hr^{-1}; $p < 0.0001$). When considering the difference in water availability between the two sites, these results are consistent with previous research where sap flow sensors were employed to characterize tree transpiration, along with other studies of ET in bioretention practices. Gazal, Scott, Goodrich, and Williams (2006) reported higher total annual transpiration in cottonwood trees grown alongside a perennial stream, where water was not limiting, than others grown near an intermittent stream, where trees exhibited greater signs of water stress due to lack of water availability. Berland et al. (2017) suggest that sustaining high ET rates in green infrastructure practices requires adequate soil moisture levels to be maintained. Relating these observations to bioretention, results from Wadzuk et al. (2015) indicated higher portions of the water balance of bioretention practices with IWS layers that maintained soil moisture could be attributed to ET. The significant differences in transpiration rates observed in the suspended pavement systems provide further evidence that maintaining a region of high soil moisture within the bioretention media profile, whether it is derived from the inclusion of an IWS layer or due to lower permeability subsoils surrounding the practice, can influence the water balance through

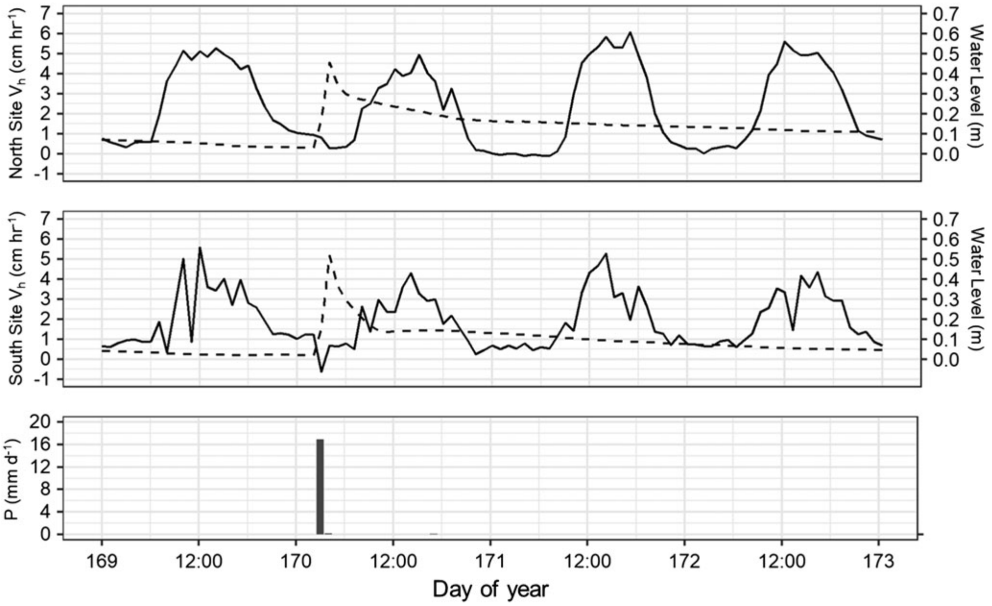

FIGURE 4 Trends in heat pulse velocities (solid line) and water level (dashed line) at suspended pavement sites following a 17-mm rain event on Day 170. Peak heat pulse velocities at both sites declined from their relative maximum values on Day 169 and recovered on Day 171 as water levels in the systems receded due to drainage

increased transpiration rates, even between individuals of the same tree species.

3.3 | Environmental influences on transpiration

One potential outlier (on Day 136) was identified in the residual-predicted plot for the north site regression model. Due to the lag terms used in the model, this reading was likely influenced by the equipment power failure that occurred from Day 132 to Day 135 at the north site, which produced a subsequently low mean daily sap flow on Day 135 after power was restored. Therefore, this point was removed from the regression model for the north site, which improved model prediction accuracy and eliminated autocorrelation from the residuals. No such outliers were identified for the south site. Parameters determined to be significant in the stepwise regression analyses using meteorological factors to model sap flow are shown in Table 2.

Regression models for both suspended pavement systems effectively predicted tree transpiration using daily averaged meteorological parameters ($p < 0.0001$). The model results suggest that vapour pressure deficit (D and lag D) and antecedent heat pulse velocity (lag V_h) explained the most variability in transpiration rates. Although not significant for the north site model, transpiration rates at the south site were significantly explained by mean daily air temperature of the previous day (lag T), though the regression coefficient was small, indicating that changes in air temperature did not produce a large change in V_h. The positive relation between D and V_h is not surprising, as evaporative losses spurred by vapour pressure differentials between the leaf and the atmosphere constitute the majority of water used by trees (Pallardy, 2008). This finding agrees with results from Chen et al. (2011), who also found that transpiration in urban trees in China was significantly controlled by D. The negative influence of antecedent D and V_h on transpiration levels in the models is also reasonable. High atmospheric water demand and correspondingly high transpiration rates limit the ability of the tree to rehydrate at night via water absorption through roots, creating decreased water availability for transpiration during the following day.

Though the regression models suggest that the same environmental factors influenced transpiration rates in both sites, the magnitude of the model parameters indicates that the response of V_h to environmental changes was different between the suspended pavement

TABLE 2 Results of regression analyses using daily averaged meteorological values (lag D and lag T) and antecedent heat pulse velocities (lag V_h) as independent variables to model sap flow (V_h)

Model parameter	North site	South site
D (kPa)	1.80	1.35
Lag D (kPa)	−1.60	−1.06
Lag T (°C)	—	−0.05
Lag V_h (cm hr^{-1})	0.80	0.77
Intercept	—	1.14
Final model	$V_h = 1.80 * D - 1.60 * \text{lag}(D) + 0.80 * \text{lag}(V_h)$	$V_h = 1.35 * D - 1.06 * \text{lag}(D) - 0.05 * \text{lag}(T) + 0.80 * \text{lag}(V_h) + 1.14$
R^2	0.79	0.80

Note. Lag terms correspond to conditions from the previous day. All model parameters were significant at $p < 0.01$.

systems. Atmospheric moisture conditions had a greater influence on transpiration rates in the north site, as changes in *D* and lag *D* produced 33% and 51% larger responses in V_h in the north site compared with the south site, respectively. With the differences in water availability between the sites established via the water-level measurements, these results suggest that stomatal regulation to limit water losses is occurring in the tree in the south site, whereas the higher water availability in the north site makes this water conservation strategy less necessary. This conclusion again aligns with findings from Gazal et al. (2006), who suggested that a lack of significant relationship between sap flow and vapour pressure deficit in trees growing in water-limited conditions (i.e., near intermittent streams) indicated the influence of stomatal control on water losses. Conversely, the authors of this study found this relationship to be significant in trees growing in nonwater-limiting environments (i.e., along perennial streams), indicating a low resistance to water losses (Gazal et al., 2006). These restrictions to transpiration responses to vapour pressure deficit likely resulted in the lower mean heat pulse velocity rate observed in the south site.

These findings may have important design implications when characterizing the influence of transpiration on bioretention hydrology. Unlike most urban settings, where characterizing tree water use is important from a resource conservation perspective (such as mitigating transpiration losses of water used for irrigation), stormwater engineers may often seek to maximize transpiration losses in bioretention practices when volume reduction is a key run-off management objective. These results suggest that volume reduction via transpiration may be reduced in a scenario where water is limiting due to stomatal regulation of water losses compared with site conditions characterized by high soil moisture and water availability, even among trees of the same species. It should be noted that prolonged saturated soil conditions impair tree function, even in highly flood tolerant species. Therefore, trees are likely to contribute more to volume losses via transpiration when higher, though not saturated, soil moisture conditions are maintained in bioretention practices, which can be achieved through design strategies such as the inclusion of IWS layers or allowing run-off to slowly percolate into underlying subsoils instead of underdrain networks (when applicable).

4 | CONCLUSIONS AND RECOMMENDATIONS

Transpiration rates of two bald cypress (*T. distichum*) trees grown in suspended pavement systems backfilled with bioretention media were studied using sap flow sensors during the summer of 2017. During the study, transpiration rates were dependent on site conditions that influenced water availability, and tree responses to environmental conditions were varied. Lower transpiration rates were observed in the more water-limited conditions of the underdrained system. Further, regression models showed that atmospheric vapour pressure demand significantly influenced transpiration rates and that water availability was connected to the degree of stomatal control on water loss. Results from this study suggest that transpiration losses are greater in bioretention systems with higher water availability. Therefore, to maximize the contribution of transpiration on run-off volume reduction, stormwater engineers should consider design strategies that promote these conditions while minimizing prolonged saturation in the upper soil layers, such as the inclusion of an internal water storage layer or promoting run-off percolation into surrounding soils in place of a perforated underdrain network, when appropriate. Future research should investigate other tree species to identify potential differences in their ability to regulate water losses when water-limiting conditions exist.

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