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Soils beneath suspended pavements: An opportunity for stormwater control and treatment

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ABSTRACT

Trees provide air quality, water quality and aesthetic benefits to urban areas. However, urban soils are frequently compacted to meet the structural stability requirements of pavements and buildings. Suspended pavement systems create an uncompacted soil volume beneath pavements in built environments to provide suitable conditions for tree root growth and structural stability for pavements. Another potential use of the soil–root matrix beneath a suspended pavement includes stormwater management. Two suspended pavement systems were constructed in Wilmington, North Carolina, USA, and runoff was routed through the root–soil matrix for detention and treatment. The two retrofits each contained 21.2 m^3 of soil volume with a crape myrtle (*Lagerstroemia indica x fauriei*) and were nearly identical. An impermeable geomembrane isolated the water quality impacts of the system and an internal water storage (IWS) layer promoted $NO_{2,3}$-N removal through denitrification. At one retrofit, 80% of runoff over the yearlong monitoring period was treated. For storms that did not generate bypass, significant mitigation of peak discharge (Q_P) was observed (62%). Pollutant concentrations of TKN, $NO_{2,3}$-N, TAN, TN, O-PO_4^{3-}, TP, TSS, Cu, Pb and Zn all decreased significantly at both retrofit sites. Effluent $NO_{2,3}$-N concentrations between the retrofit sites were not significantly different despite varying organic matter content and a substantial difference in influent $NO_{2,3}$-N concentrations. Effluent concentrations of TSS, Cu, and Zn were not statistically different between the sites, indicating consistent treatment of particulate and particulate-bound pollutants within the systems. This proof-of-concept study illustrates that the soil–root matrix beneath a suspended pavement system can be used as a stormwater control measure (SCM) to concomitantly achieve water quality, pavement stability and urban forestry goals.

1. Introduction

1.1. Trees in urban areas

Urban trees are considered valuable assets in cities worldwide (Dwyer et al., 1992; McPherson et al., 1997). They improve local climate and air quality through mitigation of the heat island effect and gaseous pollutant sequestration (Taha, 1996; Rosenfeld et al., 1998; Akbari et al., 2001; Brack, 2002; Nowak and Crane, 2002). The urban forest (Miller, 1997) can also provide better water quality at the watershed-scale by decreasing runoff volumes and pollutant loads through canopy interception (Lormand, 1988; Xiao et al., 1998; Inkiläinen et al., 2013). The aesthetic benefits of urban trees make cities more enjoyable and livable (Smardon, 1988; Tyrväinen et al., 2003). However, poor soil conditions in the urban environment can be the limiting factor for life expectancy and growth of urban trees (Craul, 1992). Subsoils adjacent to, and beneath pavements and buildings are compacted to provide structural stability, which leads to undersized or confined planting areas and tree pits (Yung, 1993; Pitt et al., 2008). While compaction does increase soil strength, root growth is inhibited, which is detrimental to tree health and lifespan (Craul, 1985; Grabosky et al., 2002; Krizek and Dubik, 1987; Yung, 1993).

1.2. Balancing structural stability, tree health, and stormwater management

Arborists, urban foresters and structural engineers have introduced the concept of a suspended pavement system over uncompacted soil to meet the concurrent needs of structural stability and urban tree health. Suspended pavements can be

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constructed of precast concrete components, piers formed and poured in place or proprietary units like the Silva Cell™ (Smiley et al., 2006; Bartens et al., 2010). These systems are designed to transfer the static and active loads of pavement, pedestrians and vehicles to an aggregate subgrade, thus creating an uncompacted soil volume that improves soil conditions for root growth. Researchers have shown that trees planted in uncompacted soil beneath pavements grow faster, are healthier in visual appearance, and create more canopy shade than trees going in compacted urban soils (Smiley et al., 2006). In light of a global progression towards the integration of gray and green infrastructure in cities (Benedict and McMahon, 2002), the uncompacted soil–root matrix of a suspended pavement system may also be used as a stormwater management facility to provide runoff volume reduction, peak discharge attenuation, and water quality treatment.

1.3. Purpose of study

The hydrologic and water quality impacts of the soil–root matrix beneath a suspended pavement have not been evaluated to-date in the peer-reviewed literature. Surface runoff can be routed to this soil–root matrix for detention and treatment through a pipe network, tree pit, or permeable pavement. In this study, two suspended pavement systems were constructed using Silva Cells™ (Fig. 1). Subsurface systems of this nature are appropriate for use in the municipally managed and maintained transportation right-of-way because they can be constructed beneath sidewalks, plazas, parking lanes, and parking areas. This study was designed to evaluate the hydrologic and water quality performance of two suspended pavement systems constructed beneath a plaza area and sidewalk in Wilmington, North Carolina, USA.

1.4. Treatment processes

The soil and tree root matrix of a suspended pavement system has stormwater treatment processes analogous to a bioretention system when a similar soil media is used. Water quality evaluations of bioretention systems have shown particulate pollutants are sequestered by the engineered filter media. Heavy metals and total suspended solids (TSS) have consistently been retained by bioretention systems via filtration, sedimentation and adsorption; mass load reductions of total suspended solids (TSS), copper (Cu), lead (Pb) and zinc (Zn) are usually greater than 85% (Davis et al., 2003; Hunt et al., 2008; Li and Davis, 2009; Brown and Hunt, 2011). Particle-bound phosphorus (PBP) is captured at the soil media surface, but low soil test phosphorus (P-index) is necessary to ensure dissolved orthophosphate ($O\text{-}PO_4^{3-}$) is not exported (Hunt et al., 2006; Hatt et al., 2009).

Nitrogen retention is influenced by particulate capture, vegetative uptake and biological transformations. Organic nitrogen (ON) and total ammoniacal nitrogen (TAN) (thus, total kjeldahl [TKN]) are typically sequestered by bioretention systems with under drains at the bottom of the cross-section, but nitrate-nitrogen ($NO_{2,3}$-N) tends to migrate through the filter untreated (Davis et al., 2003; Dietz and Clausen, 2005; Dietz, 2007; Hunt et al., 2008; Brown and Hunt, 2011). Unless specifically designed otherwise, bioretention systems are predominantly aerobic systems and transformations of ON and TAN to $NO_{2,3}$-N occur readily through mineralization, ammonification and nitrification during inter-event dry periods (Kim et al., 2003; Lucas and Greenway, 2011; Hunt et al., 2012). $NO_{2,3}$-N stored in the soil media is then flushed from the system during the next precipitation event, resulting in higher effluent concentrations of $NO_{2,3}$-N than were observed in untreated influent runoff (Kim et al., 2003; Davis et al., 2001Davis et al., 2006; Hunt et al., 2006, 2008; Hatt et al., 2009). Hunt (2003) and Kim et al. (2003) proposed the internal water storage (IWS) layer to increase $NO_{2,3}$-N removal by creating a saturated layer of soil within bioretention systems, which allows the system to function as a bioreactor promoting denitrification (Moorman et al., 2010; Schipper et al., 2010). Several studies have shown improved $NO_{2,3}$-N conversion on a concentration basis with the simple design modification (Dietz and Clausen, 2006; Bratieres et al., 2008; Passeport et al., 2009; Collins et al., 2010; Brown and Hunt, 2011; Luell et al., 2011; Lucas and Greenway, 2011).

2. Materials and methods

2.1. Site description

The study site was located in Wilmington, North Carolina, USA. Wilmington is located in the southern coastal plain between the Cape Fear River and the Atlantic Ocean. On average, Wilmington International Airport (ID# 319457) receives 1448 mm of rainfall annually. Normal temperatures in summer and winter range from

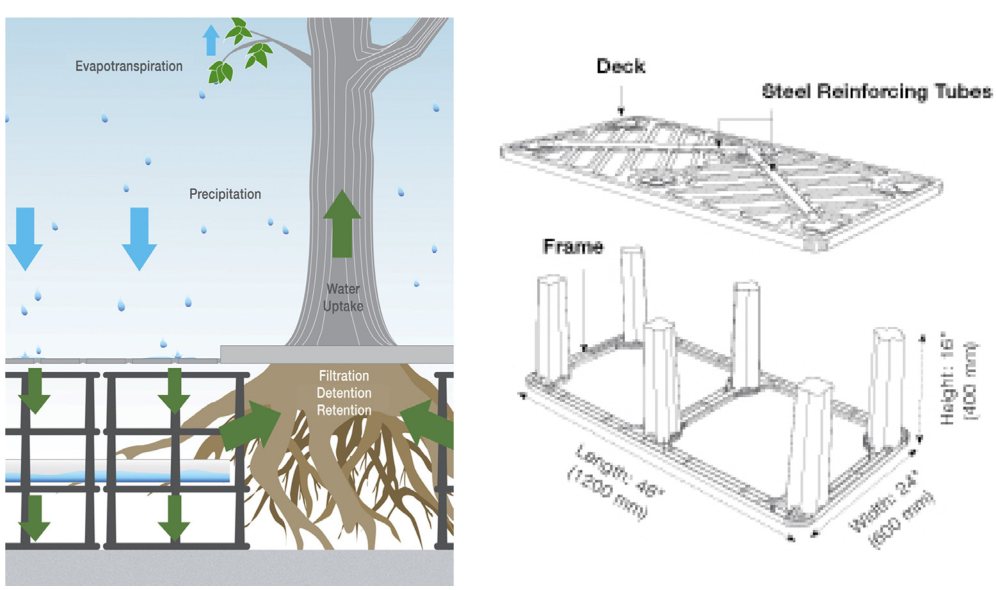

Fig. 1. Schematic and detail of the Silva Cell™ suspended pavement system (image courtesy of DeepRoot Green Infrastructure, LLC).

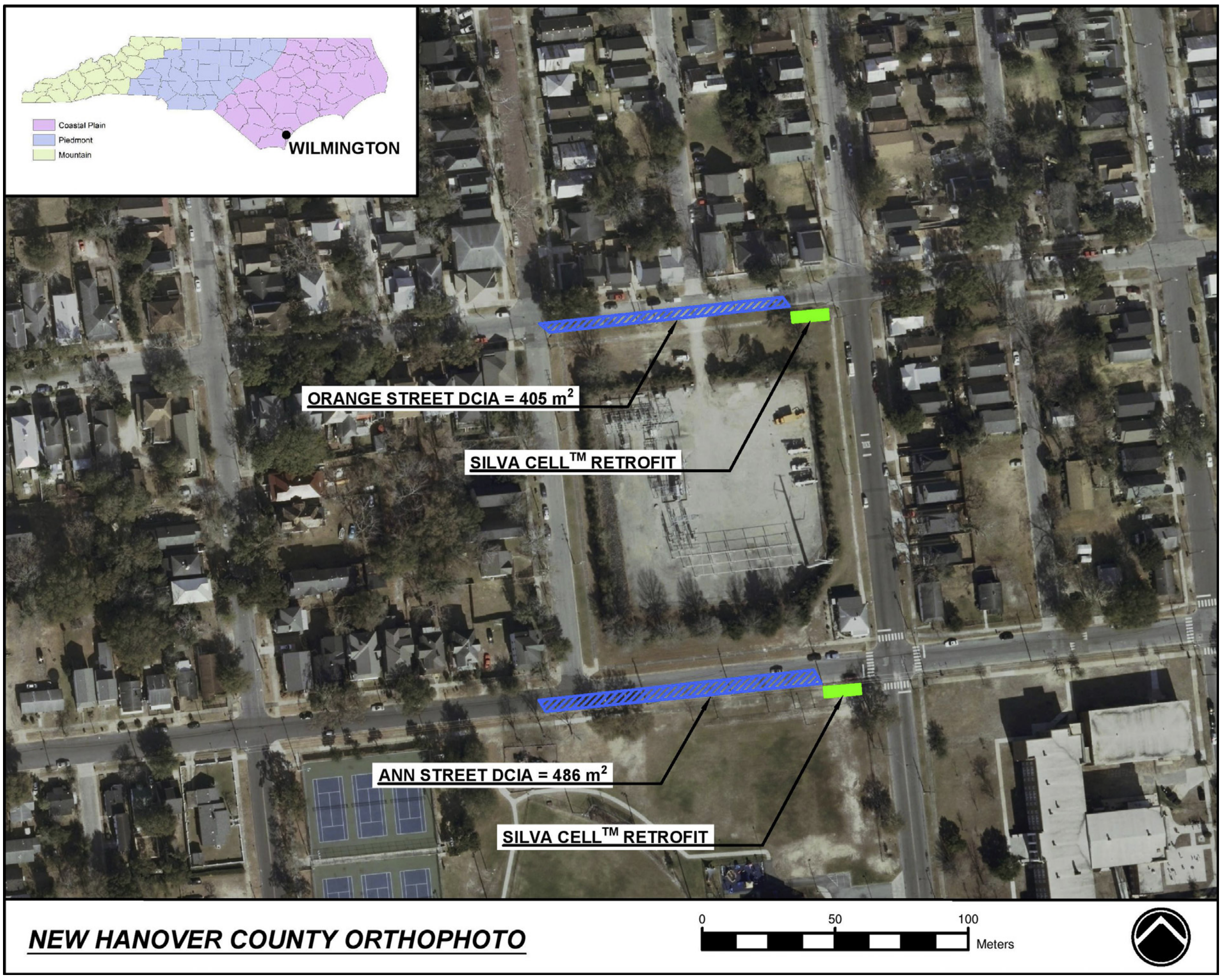

Fig. 2. Location of study within North Carolina, aerial view of watersheds (hatched areas) and suspended pavement retrofits.

Table 1
Summary of study drainage areas and suspended pavement design components.

Parameter	Drainage area summary	
	Orange street	Ann street
Drainage area	2,242 m^2	2,873 m^2
DCIA	405 m^2	486 m^2
Imperviousness	100%	100%
Slope	2.5%	1.8%
Soil series	Leon (Le)	Rimini (Rm)
USDA soil class	Sand	Sand
SCM location	N 34.233660 W 77.936588	N 34.232327 W 77.936459
Receiving water body	Burnt Mill Creek	
River basin	Cape Fear	
Silva Cell™ Design summary		
Silva Cell™ Frames	68	
Silva Cell™ Decks	34	
Surface Area	27.6 m^2	
Soil Volume	21.2 m^3	
Loading Ratio[a]	15:1	18:1
Soil media composition[b]		
Gravel	4.5%	0.0%
Sand	87.4%	87.3%
Silt	7.0%	8.7%
Clay	1.1%	4.0%
Organic matter	3%	6%

[a] DCIA/SCM surface area.
[b] Gravel, sand, silt and clay gradations are by volume; organic matter is by weight.

23.9 °C to 27.2 °C and 7.7 °C to 12.7 °C, respectively (State Climate Office of North Carolina, 2012). Two directly connected impervious areas (DCIA), located on adjacent city blocks, were selected for subsurface treatment of runoff using the suspended pavement system (Fig. 2). The DCIAs (street surface) of the Orange Street and Ann Street retrofit sites were similar at 405 m^2 and 486 m^2, respectively (Table 1). Average slopes in the watersheds were 2.5% and 1.8%, and the underlying soils were classified as sand.

Installation of the two suspended pavement systems occurred from mid-June to mid-July 2012. Silva Cell™ units were placed on a layer of aggregate with underdrains and filled with soil media to a level 5 cm below the decks. An additional layer of aggregate was placed on top of the decks and the system was partially overlain with sidewalk. Both systems were lined with an impermeable geomembrane. This is atypical for suspended pavement and bioretention installations, as it is often desirable to exfiltrate as much influent runoff as possible from SCMs. Influent runoff could only leave the system as drainage or evapotranspiration. The geomembrane was used to isolate the systems and to ensure adequate water quality samples were collected. Finally, a crape myrtle (*Lagerstroemia indica x fauriei*) was planted in a tree opening such that the roots could spread out into the uncompacted soil within each uncompacted soil volume

Runoff was routed to the soil matrix beneath the pavement by installing a new catch basin in the existing gutter on the upslope end of each system. A single 15 cm diameter PVC pipe (with a debris rack to prevent clogging) conveyed runoff from the catch

Table 2
Laboratory analytical methods.

Pollutant	Pollutant name	Analytical method	PQL[a]	Unit
$NO_{2,3}$-N	Nitrate + nitrite nitrogen	SM 4500-NO3-F[b]	0.006	mg/L
TKN	Total kjeldahl nitrogen	EPA 351.1[c]	0.38	mg/L
TAN	Total ammoniacal nitrogen	SM 4500-NH3-H[b]	0.006	mg/L
ON	Organic nitrogen	=TKN−TAN	NA	mg/L
TN	Total nitrogen	=TKN + $NO_{2,3}$-N	NA	mg/L
O-PO_4^{3-}	Orthophosphate	SM 4500-P-F[b]	0.006	mg/L
TP	Total phosphorus	SM 4500-P-F[b]	0.01	mg/L
PBP	Particle bound phosphorus	=TP−O-PO_4^{3-}	NA	mg/L
TSS	Total suspended solids	SM 2540 D[b]	5–10	mg/L
Cu	Copper	EPA 200.8[c]	2	mg/L
Pb	Lead	EPA 200.8[c]	2	mg/L
Zn	Zinc	EPA 200.7[c]	10	mg/L

[a] Practical quantification limit.
[b] Eaton et al. (1995).
[c] United States Environmental Protection Agency (USEPA) (1993)

basin to the Silva Cell™ system. Upon entering the soil media the single inlet pipe was split to two perforated 15 cm diameter PVC pipes, located at the top of the cross-section. Influent runoff passed vertically through the uncompacted soil media, which acted as a filter. Three 10 cm perforated PVC pipes drained the system. The underdrains were fitted with a 90^0 upturned elbow to create an IWS layer 40 cm in thickness, and were tied into the storm sewer network via existing catch basins downslope of the retrofits. This configuration allowed bypass that occurred during large storm events to continue along the curb line to an existing catch basin. NC Standard bioretention media was installed at both sites, with organic matter content varying at Ann Street and Orange Street at 6% and 3% by weight, respectively (Table 1) (North Carolina Department of Environment and Natural Resources (NCDENR), 2009). Particle size analysis (PSA) using the hydrometer method (Gee and Bauder, 1986) was used to determine the gradation of the soil media. The organic matter source was shredded pine bark.

2.2. Monitoring design

Two HOBO™ tipping bucket rain gauges were installed free of overhead obstructions at both sites. A single manual rain gauge was also installed at the Orange Street site. ISCO 6712™ automated samplers were utilized at the inlets and outlets of each retrofit. At the inlets, the ISCO 6712™ samplers were enabled and paced by rainfall depth recorded by the two tipping bucket gauges. Flow-weighted, composite samples were suctioned from intakes placed at the base of the new catch basins just below the invert of the inlet pipe. The inlet catch basins were cleaned approximately every two months to prevent sediment, leaf litter and debris from accumulating and fouling the sampler intakes. At the outlets, a 45° v-notch weir and weir box was installed inside the existing catch basin and the sampler intake was placed at the base of the weir box in an area of well mixed flow. ISCO 730™ bubbler flow modules monitored discharge and total runoff volume by measuring stage over the weir invert at two minute intervals.

2.3. Sampling protocol

The ISCO 6712™ portable samplers were programmed to suction 200 mL aliquots per incremental rainfall depth and were deposited into 1 L bottles. A minimum of 10 aliquots (2 L) was needed for a full set of water quality analyses to be conducted. The

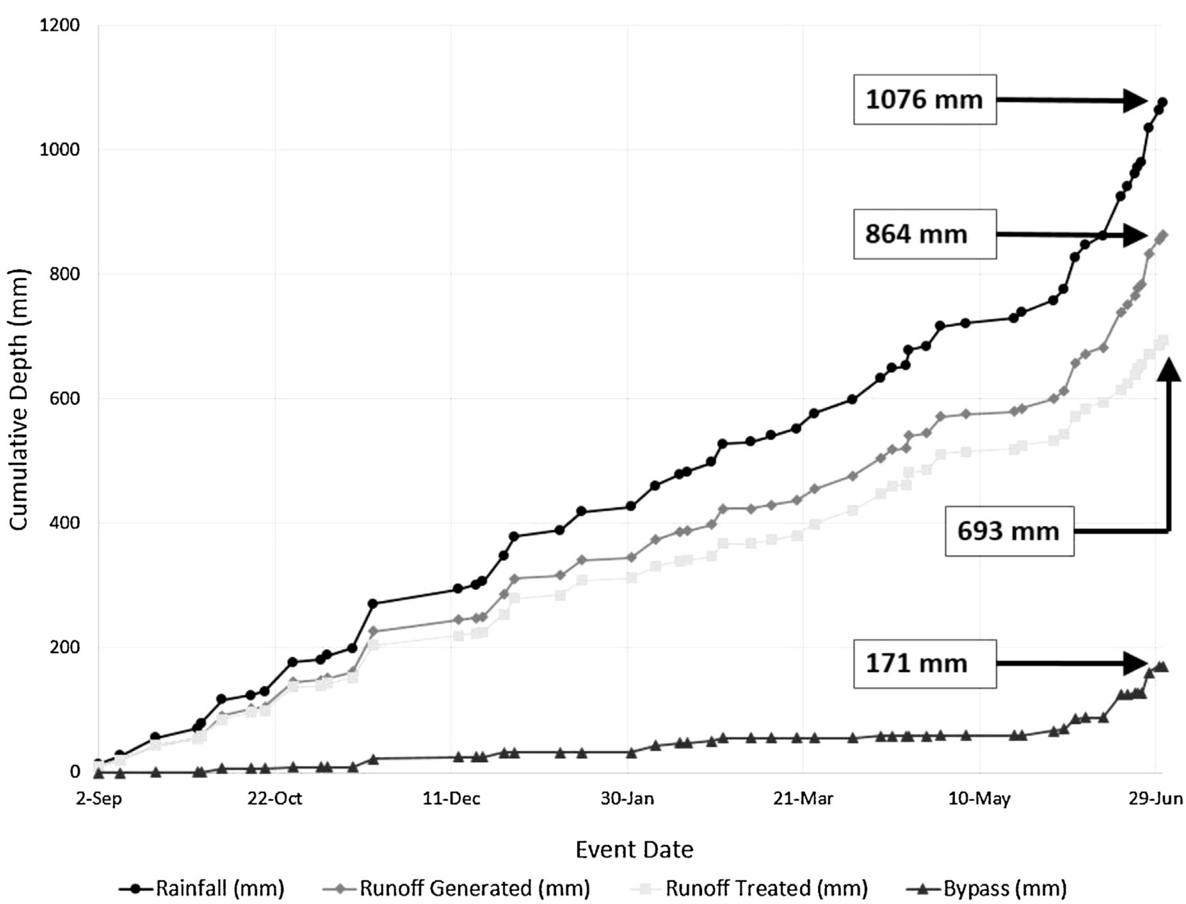

Fig. 3. Cumulative fate of runoff at the Ann Street site.

samplers were programmed to collect samples from rainfall events ranging from 5 mm to 64 mm. Adjustments were made to the sampler programs if a larger rainfall event was expected. Water quality samples were collected within 24 h of a rainfall event. TSS, TKN, TAN, $NO_{2,3}$-N, TP, and O-PO_4^{3-} samples were analyzed by the North Carolina Center for Applied Aquatic Ecology at NCSU in Raleigh, NC. Total nitrogen (TN) concentrations were calculated by summing TKN and $NO_{2,3}$-N; organic nitrogen (ON) concentrations were determined by subtracting TAN from TKN for each sampled storm event. PBP concentrations were determined by subtracting O-PO_4^{3-} from TP. Total concentrations of Cu, Pb and Zn samples were analyzed by the North Carolina Department of Environment and Natural Resources (NCDENR) Environmental Chemistry Lab in Raleigh, NC. Both labs were located approximately 210 km (130 mi) from the study site. Laboratory analytical methods are listed in Table 2.

2.4. Data processing and statistical analysis

Hydrologic data were reviewed using Flowlink Version 5.0 software (ISCO, 2005) and compared to notes made in the field log. Discrete rainfall events were separated by a 6-h antecedent dry period. Influent runoff volume (RO_V) was calculated using the SCS curve number method (Pandit and Heck, 2007). Influent peak discharge (Q_P) was determined using five-minute peak rainfall intensities and a rating curve developed from 1.14 yr of hydrologic data collected at a very similar drainage area (urban residential street) in Wilmington located just two blocks west of the study area (Page et al., 2015). Bypass was calculated when inflow volumes were greater than the sum of measured outflow volume and storage volume within the soil media. Available storage volume within the soil media was considered to be the difference between the water free pore space and field capacity. Drawdown rates (D_R) were defined as the quotient of the change in water table depth to time and measured in a well internal to the Orange Street retrofit. For pollutant concentrations that were less than the practical quantification limit (PQL), one-half the value of the PQL was substituted for calculations and statistical analysis.

SAS Version 9.3™ was used for statistical analyses (SAS, 2012). All statistical tests were conducted using $\alpha = 0.05$. The hydrologic and water quality data sets were checked for normality using the Shapiro–Wilk goodness-of-fit test. If differences in paired inlet and outlet data points were not normally distributed, the differences were log transformed and tested again. Paired differences that were normally distributed were tested with a paired *t*-test. The Wilcoxon signed rank test was used for non-normally distributed data. Changes in hydrologic and water quality metrics were calculated using Eq. (1).

$$\text{Change}(\%) = \left[\frac{X_{OUT}}{X_{IN}} - 1\right] \times 100\% \quad (1)$$

where, X_{IN} = influent parameter and X_{OUT} = effluent parameter.

For comparisons between effluent concentrations from the Ann Street and Orange Street sites, the non-paired Student's *t*-test was used when the data sets were normally or log-normally distributed. The Mann–Whitney test was used for comparison of non-normally distributed effluent concentration data sets.

3. Results and discussion

3.1. Hydrology

The Ann Street retrofit was monitored from September 2012 through June 2013. Over the 10-month period, 53 storms between 3 and 72 mm were recorded for a total of 1076 mm of rainfall. Mean and median rainfall depths were 20 mm and 15 mm, respectively.

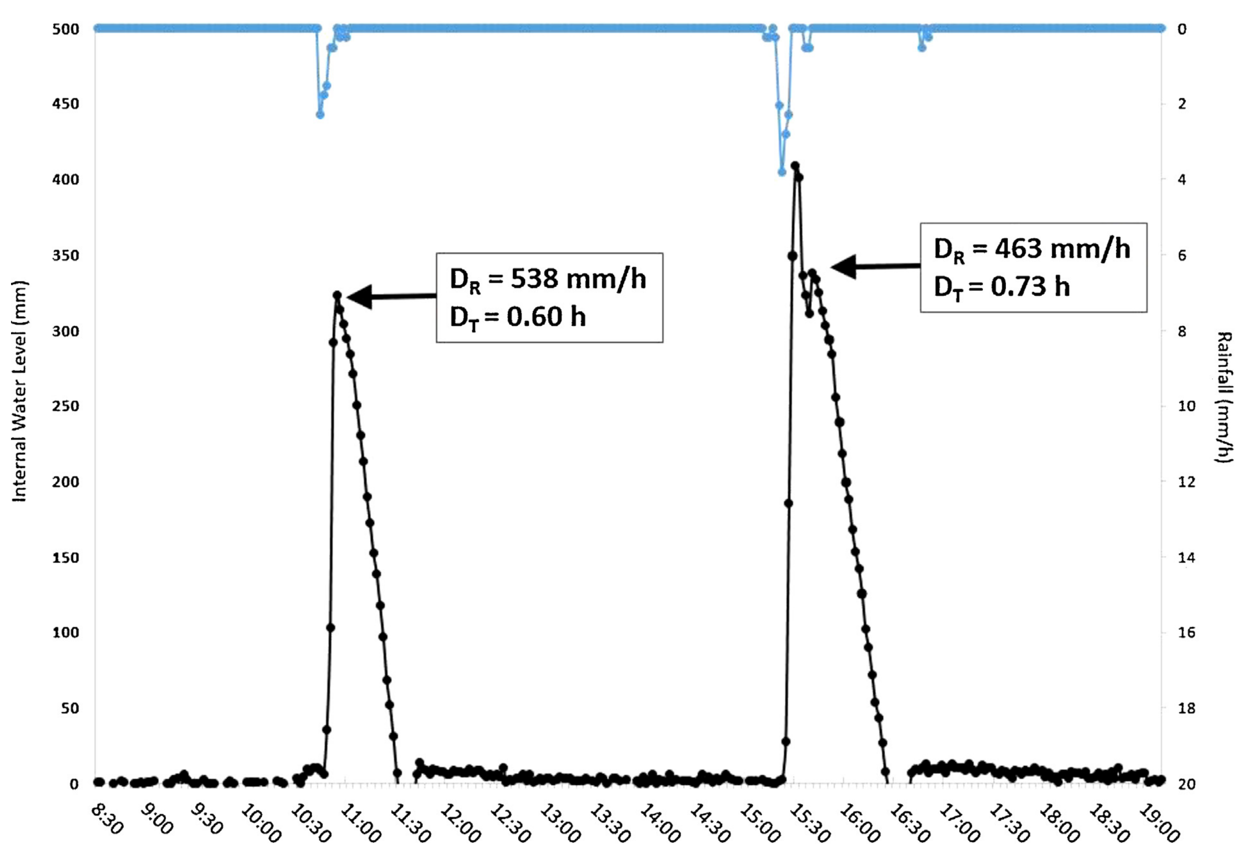

Fig. 4. Orange Street internal water level from 22 June to 24 June, 2013 (0 mm = top of IWS; 410 mm = top of suspended pavement system).

At the inlet, an estimated 864 mm of runoff was generated by the DCIA and 693 mm (80%) was treated by the soil media beneath the suspended pavement (Fig. 3). Thus, 20% of the cumulative runoff estimated at the inlet bypassed the system and 40% (21 of 53) of the rainfall events generated bypass. Bypass appeared to be linked to rainfall depth rather than rainfall intensity. There was a significant difference in rainfall depth using bypass occurrence as a basis while there was no apparent difference in rainfall intensity. During larger storms the soil media likely became saturated resulting in lower internal flow rates through the soil media and bypass. As described previously, the base of the suspended pavement retrofits was lined with an impermeable geomembrane, eliminating exfiltration. There were 21.2 m^3 of soil media within the system (Table 1), half (10.6 m^3) of which remained saturated due to the designed IWS layer. Assuming the water free pore space and field capacity of the soil media was 34% and 18%, respectively (United States Department of Agriculture (USDA), 1955; Brown et al., 2013), there were 1.7 m^3 of void space available prior to a storm if the soil media above the IWS layer was at field capacity. This storage volume is relatively small in comparison to the RO_V supplied by the contributing drainage area (25 mm of rainfall = 9.7 m^3 of runoff, 38 mm of rainfall = 15.8 m^3 of runoff and 5 mm of rainfall = 1.7 m^3 of runoff). With this design, the soil media beneath the suspended pavement functioned primarily as a flow-through filter, and as anticipated, no change was observed in RO_V for events that did not generate bypass. However, significant Q_P mitigation was observed; mean Q_P decreased 62% from 3.7 L/s to 1.4 L/s and the inner quartile range of effluent flow rates was 1.1 L/s to 1.7 L/s. Outflow rates were very consistent despite a wide range of inflow rates, which may have been regulated by the saturated hydraulic conductivity of the soil media. Greater outflow rates were observed during the first two months of the monitoring period, suggesting some settling of the soil media occurred post-construction.

3.2. Internal drawdown rates

Internal drawdown rates (D_R) were measured for the soil media above the IWS layer at the Orange Street site. Median D_R was 420 mm/h and the median dewatering time (D_T) was 0.7 h, which resulted in low hydraulic residence times (T_{HR}) within the soil

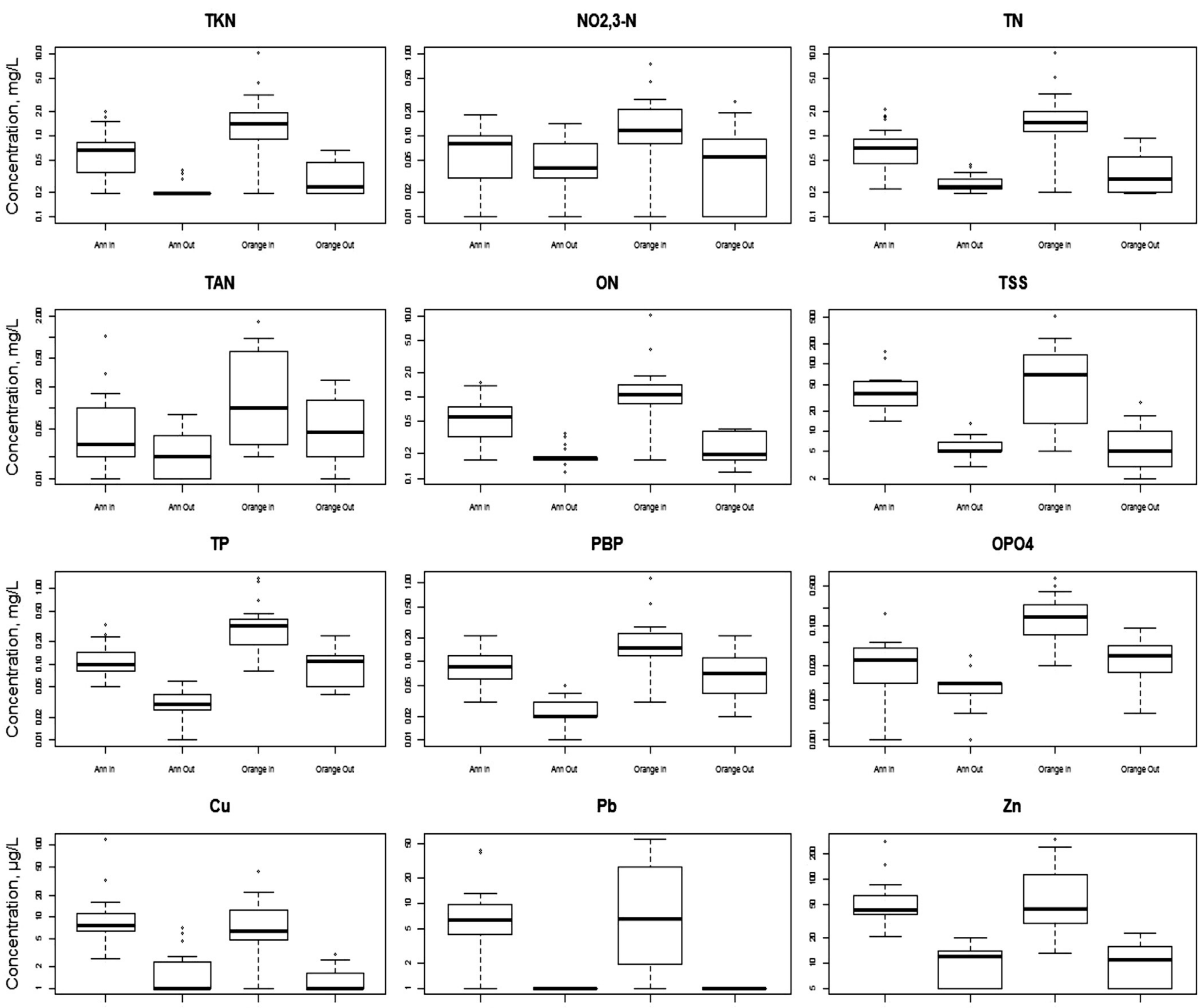

Fig. 5. Boxplot summary of pollutant concentration distributions for Ann Street and Orange Street sites in Wilmington, NC.

media and a "flashy" hydrologic response (Fig. 4). Both D_R and D_T were substantially faster than rates and times typically reported for bioretention systems in North Carolina (Wardynski and Hunt, 2012). D_R for optimal nitrogen and phosphorus removal is recommended to be between 30 and 100 mm/h (Hunt et al., 2012). The increased D_R may be caused by non-uniform compaction of the soil media. The vertical posts of the Silva Cell™ make it difficult to place the soil media in uniform lifts. Extra time and care is necessary during placement of the soil media around the vertical posts and frames to reach a more uniform level of compaction and drainage behavior. Despite the 420 mm/h D_R and consequently low T_{HR}, water quality treatment of nitrogen and phosphorus remained high, as described in subsequent sections.

3.3. Water quality – pollutant concentrations

From September 2012 to July 2013, 21 and 19 sets of paired water quality samples were collected from the Ann Street and Orange Street sites, respectively. In general, influent pollutant concentrations at Orange Street were greater than those observed at Ann Street, and concentrations of all pollutants sampled at both sites significantly decreased from inlet to outlet (Fig. 5). TKN concentrations at the Ann Street and Orange Street sites decreased significantly 71% and 84%, respectively. Mean effluent TKN concentrations at Ann Street were 0.22 mg/L and 0.33 mg/L at Orange Street. These effluent concentrations were very similar to those reported in a recent North Carolina bioretention study (Luell et al., 2011). The decrease in TKN concentrations was primarily due to particulate ON retention, though TAN concentrations also decreased at both sites. At the Orange Street site, $NO_{2,3}$-N concentrations significantly decreased by 60% from 0.17 mg/L to 0.07 mg/L. At Ann Street, a lesser but still significant 35% decrease in $NO_{2,3}$-N concentration occurred, potentially due to lower influent $NO_{2,3}$-N concentrations. There was no statistical difference in effluent $NO_{2,3}$-N concentrations despite varying organic matter content within the two retrofits (Fig. 5). Effluent $NO_{2,3}$-N EMCs (0.05 mg/L and 0.07 mg/L) were very low compared to other bioretention studies (Davis et al., 2006; Hunt et al., 2008; Bratieres et al., 2008; Brown and Hunt, 2011). Inclusion of the IWS layer and impermeable geomembrane likely enhanced conversion of $NO_{2,3}$-N to N_2 through denitrification (Bratieres et al., 2008; Passeport et al., 2009; Lucas and Greenway, 2011; Brown and Hunt, 2011). In this study, runoff remained ponded in the IWS layer during inter-event dry periods under typically reduced conditions and was flushed from the system during subsequent precipitation events, which would lead to lower effluent $NO_{2,3}$-N concentrations.

TP concentrations significantly decreased by at least 72% at both sites. Effluent TP EMCs were 0.03 mg/L and 0.11 mg/L at Ann Street and Orange Street, respectively. At Ann Street, mean influent concentrations were relatively low (0.12 mg/L) and less than a previously suggested irreducible concentration for TP (Strecker et al., 2001). In bioretention systems, TP removal has been linked to TSS retention (since the majority of TP is particulate-bound), which was greater than 86% at both sites in Wilmington (Fig. 5). Effluent TSS concentrations were not significantly different. Removal of dissolved O-PO_4^{3-} was 70% and 82% at the two sites; effluent concentrations were below 0.03 mg/L at both sites. O-PO_4^{3-} was likely captured in the upper portions of the soil media via sorption to soil particles, otherwise it would have been flushed from the system under reduced redox conditions created by the anoxic IWS

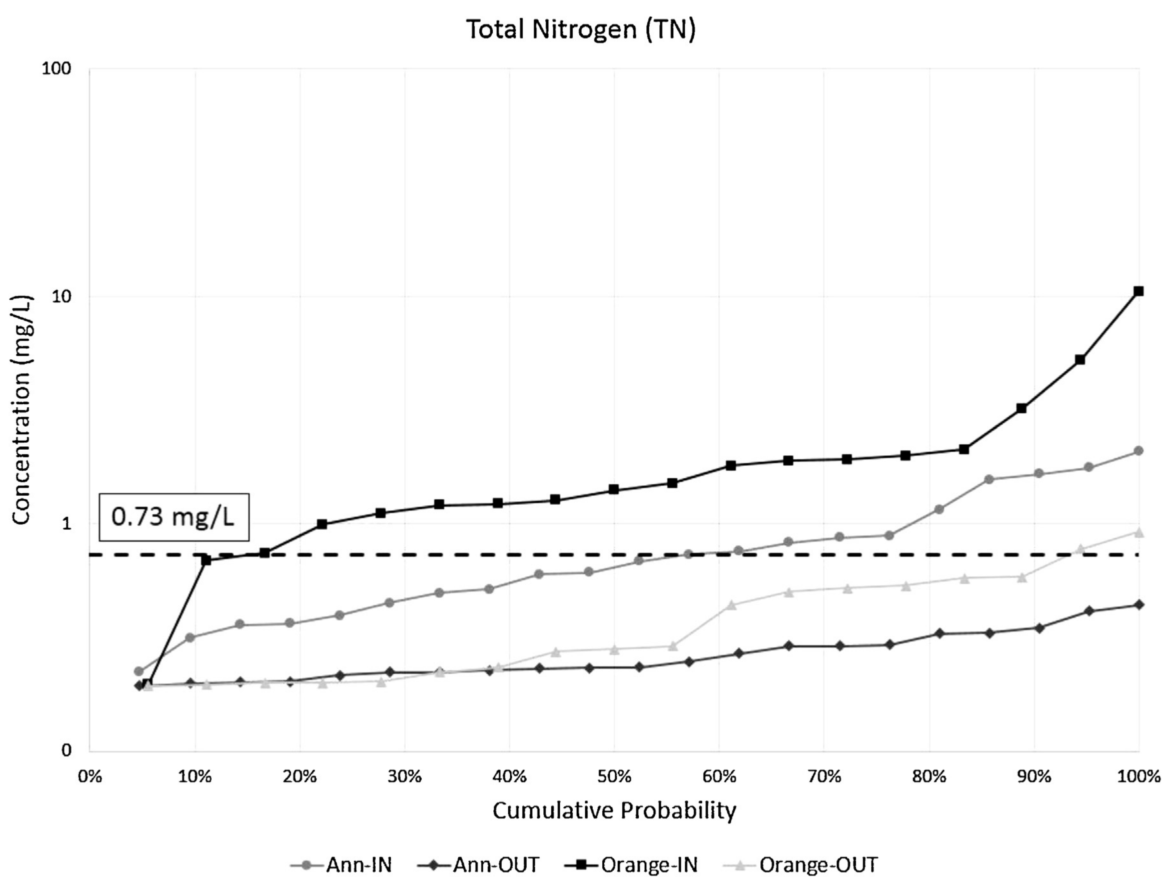

Fig. 6. Cumulative probability plots for effluent TN concentration with "good" water quality threshold in NC coastal plain as described by McNett et al. (2010).

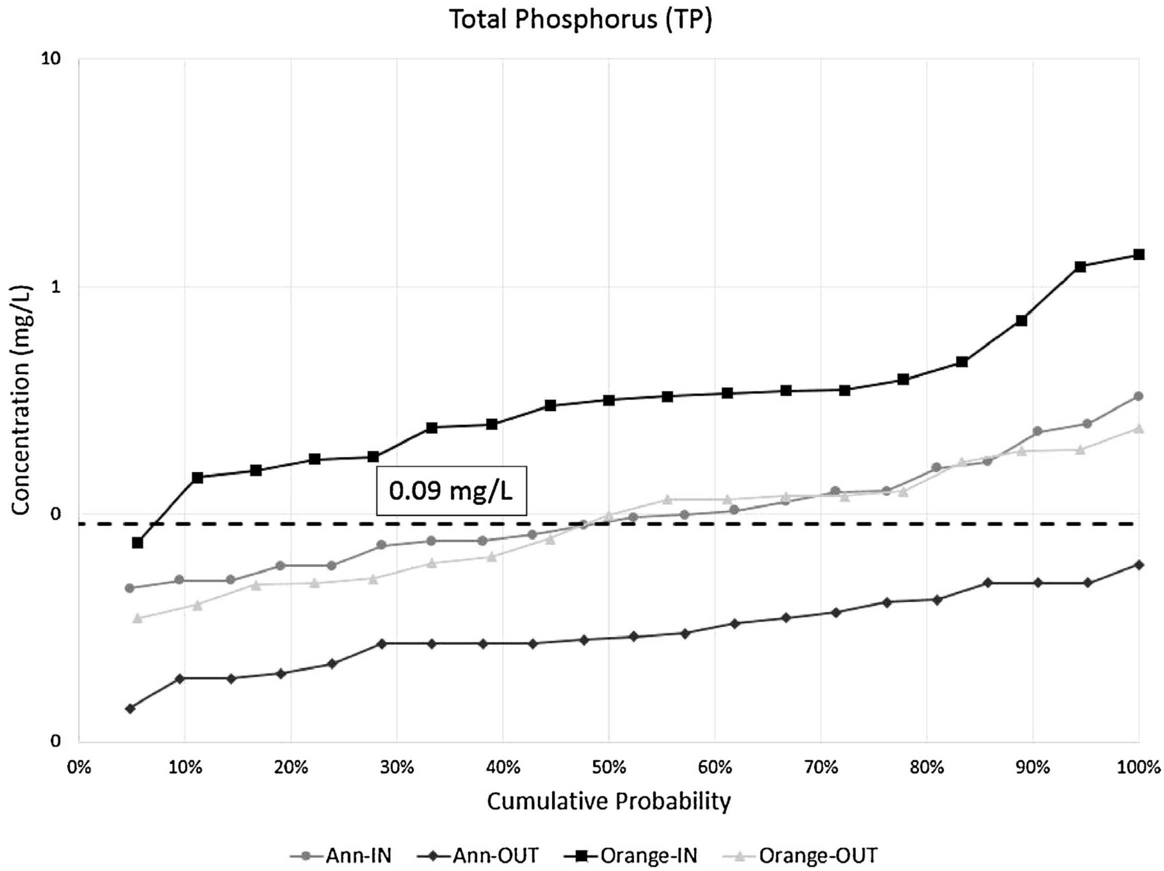

Fig. 7. Cumulative probability plots for effluent TP concentration with "good" water quality threshold in NC coastal plain as described by McNett et al. (2010).

layer (Dietz and Clausen, 2006; Hunt et al., 2012). Concentrations of Cu, Pb, and Zn at both sites significantly decreased (86–94%) (Fig. 5). Effluent concentrations of each heavy metal were not statistically different between the Ann Street and Orange Street retrofits. Cu and Pb effluent concentrations were similar to those observed by Davis (2007) from two Maryland BRCs, while effluent Zn concentrations were substantially less than those reported in that study.

3.4. Effluent pollutant concentrations and in-stream biota

Benthic macro invertebrates are often used to assess water quality impairment in streams and have been used to establish effluent nutrient concentration thresholds for SCMs (Barbour et al., 1999). McNett et al. (2010) use qualitative benthic macro invertebrate health and corresponding quantitative in-stream nutrient concentrations in North Carolina to establish water quality thresholds. "Good" water quality thresholds corresponding to the presence of sensitive benthos in coastal North Carolina streams for TN and TP were 0.73 mg/L and 0.09 mg/L, respectively. Cumulative probability plots show that all effluent TN and TP concentrations at the Ann Street site were less than the "good" water quality thresholds (Figs. 6 and 7). At Orange Street, 88% of effluent TN concentrations and 44% of TP concentrations were less than 0.73 mg/L and 0.09 mg/L, respectively.

4. Summary and conclusions

Suspended pavement systems provide dual functionality: structurally supporting pavements and improving urban tree health. This proof-of-concept study illustrated that stormwater can be routed to an uncompacted engineered soil beneath a suspended pavement for detention and treatment. At the Ann Street site, 80% of runoff estimated at the inlet was captured and treated by the soil–root matrix, and for storms that did not generate bypass, significant mitigation of peak flow rate was observed (62%). In general, pollutant removal and effluent concentrations observed in this study were similar to those reported for bioretention. Pollutant concentrations of TKN, $NO_{2,3}$-N, TAN, TN, O-PO_4^{3-}, TP, TSS, Cu, Pb and Zn at both monitoring sites decreased significantly following treatment. Additional research is needed to refine design guidance and provide a regulatory framework for the use of soil beneath suspended pavements to meet stormwater treatment and tree health goals. Future studies may include evaluations of unlined systems that allow exfiltration over well-drained and poorly drained soils, systems without saturated layers, differing hydraulic loading ratios (directly connected impervious area: soil–root matrix surface area), and long term growth rates of trees planted in systems capturing stormwater. For municipalities with existing minimum tree rooting volume standards (City of Denver, 2011; City of Raleigh, 2014), using a suspended pavement system as an SCM will aid in meeting stormwater management and silviculture requirements.

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