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Research article

Hydrologic and water quality performance of permeable pavement with internal water storage over a clay soil in Durham, North Carolina

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ABSTRACT

Permeable pavement is an effective tool for improving stormwater hydrology and water quality when sited over soils with high infiltration rates, but its efficacy over less permeable soils is uncertain. This study examined permeable pavement performance when built over a low-conductivity, clay soil. Four parking stalls (50 m^2 total area) were retrofitted with permeable interlocking concrete pavement (PICP) to treat 15.2 m^2 of contributing impervious area (0.3:1 run-on ratio). Using an elevated underdrain, the site incorporated a 150-mm internal water storage (IWS) zone to increase exfiltration and promote anaerobic conditions for denitrification. From March 2014–April 2015, 22% of influent runoff volume was reduced via exfiltration and evaporation. Inter-event drawdown of the IWS zone created storage to capture and exfiltrate more than 70% of the runoff volume from precipitation events less than 8 mm, and peak flows were significantly reduced (median 84%). Relative to stormwater runoff from a nearby impermeable asphalt reference watershed, the permeable pavement produced significantly lower event mean concentrations (EMCs) of all pollutants except nitrate, which was significantly higher. Permeable pavement effluent and reference watershed runoff were 99%, 68%, and 96% different for total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP), respectively. Significantly lower permeable pavement effluent EMCs for copper (Cu, 79%), lead (Pb, 92%) and zinc (Zn, 88%) were also observed. The median effluent concentrations of TN (0.52 mg/L), TP (0.02 mg/L), and TSS (7 mg/L) were all very low relative to the literature. Sampling of nitrogen species in the IWS zone 12, 36, 60, and 84 h post-rainfall was done to better understand mechanisms of nitrogen removal in permeable pavement; results indicated denitrification may be occurring in the IWS zone. Effluent pollutant load from the permeable pavement was at minimum 85% less than from nearby untreated asphalt runoff for TP, TSS, Cu, Pb, and Zn, and was 73% less for TN. Permeable pavements built over low-permeability soils with internal water storage can considerably improve long-term hydrology and water quality.

1. Introduction

Federally promulgated stormwater regulations have led thousands of communities across the United States to install stormwater control measures (SCMs) to meet water quality and quantity goals (USEPA, 2009). Permeable pavement is a popular SCM because it is easily retrofitted and can be parked upon. In typical designs, runoff infiltrates the permeable surface layer and is temporarily stored in an aggregate subbase; runoff is then either exfiltrated (e.g., lost to the underlying soil) or discharged to receiving surface waters via an underdrain. In addition to reducing pollutant loads to receiving streams through exfiltration, permeable pavements have been shown to capture and treat many pollutants (Bean et al., 2007; Collins et al., 2010; Drake et al., 2014a).

Studies on permeable pavement have mostly examined the hydrologic benefit of systems located over soils with high infiltration rates (e.g., Brattebo and Booth, 2003; Bean et al., 2007; Gilbert and Clausen, 2006; Pratt et al., 1995; Roseen et al., 2012; Rushton, 2001). Under these circumstances, permeable pavements provide substantial volume and peak flow mitigation via storage followed by exfiltration (Abbot and Comino-Mateos, 2003; Bean et al., 2007; Roseen et al., 2012; Wardynski et al., 2012). Less research has been done on permeable pavement systems sited over clay soils, where exfiltration is reduced (often substantially) due to low soil saturated hydraulic conductivity [K_{sat}] (Drake et al., 2014b; Dreelin et al., 2006; Fassman and Blackbourn, 2010; Tyner et al., 2009; Winston et al., 2018). These

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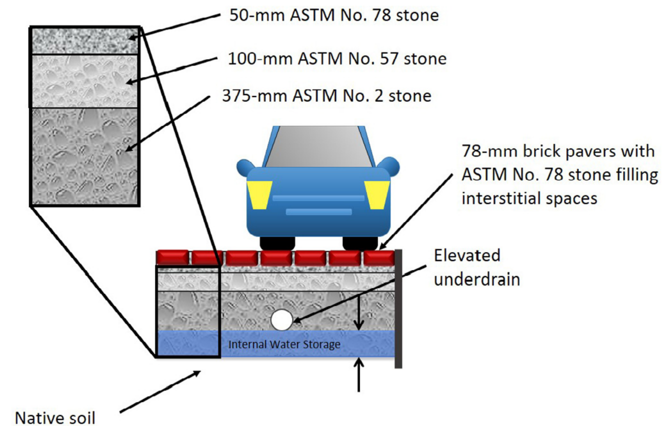

Fig. 1. Schematic cross-section of permeable pavement with an internal water storage zone.

studies suggest hydrologic mitigation may still be viable over Hydrologic Soil Group (HSG) C and D soils, with observed volume reductions of up to 53%.

Performance of permeable pavements receiving run-on from adjacent impervious areas, an increasingly implemented design feature (e.g., NCDEQ, 2012; ODNR, 2006), has been infrequently documented (Winston et al. 2016a, 2018; Selbig et al., 2017). Research is thus needed to assess the hydrologic mitigation provided by permeable pavements with higher run-on ratios. The drainage configuration (i.e., how the underdrain is designed/installed) also impacts hydrologic performance. Wardynski et al. (2012) found the inclusion of an internal water storage (IWS, Fig. 1) zone within the aggregate subbase increased exfiltration into the *in situ* sandy loam soils by 23%. Implementing IWS may increase exfiltration from permeable pavements located over clay soils, but has not yet been studied.

The permeable pavement surface layer strains sediment and particulate-bound pollutants by physical filtration while the aggregate layers promote sedimentation. Treatment via adsorption, biological degradation, and chemical transformation is also possible as runoff infiltrates the pavement (Pratt et al., 1999; Franks et al., 2014). Many studies have documented significant reductions in pollutant concentrations of total suspended solids (Legret and Colandini, 1999; Rushton, 2001; Fassman and Blackbourn, 2011; Roseen et al., 2012; Drake et al., 2014b), total phosphorus (Bean et al., 2007; Roseen et al., 2012; Drake et al., 2014a) and metals (Legret and Colandini, 1999; Rushton, 2001; Bean et al., 2007; Roseen et al., 2012; Drake et al., 2014a). Removal of dissolved pollutants [e.g., nitrate/nitrite-nitrogen ($NO_{2,3}$-N) and orthophosphate (O-PO_4^{3-})] is less assured (Bean et al., 2007; Collins et al., 2010; Roseen et al., 2012). Both Collins et al. (2010) and Drake et al. (2014a) reported an increase in $NO_{2,3}$-N coupled with a decrease in total ammoniacal nitrogen, indicating nitrification was occurring in the aggregate base. While an IWS zone can foster denitrification in bioretention by creating anaerobic conditions (Kim et al., 2003; Passeport et al., 2009), this design feature has not yet been studied for its effect on water quality in permeable pavements. Given that denitrification requires the presence of denitrifying bacteria and a sufficient source of organic carbon (Birgand et al., 2007), there is uncertainty as to whether permeable pavement fosters this environment. The objective herein was to examine the hydrology and water quality of a retrofitted permeable pavement situated over a low-permeability clay soil with run-on and incorporating an IWS zone.

2. Methodology

2.1. Site description

The study site was located at Piney Wood Park in Durham, North Carolina. Durham is a city in the Piedmont of North Carolina with an average annual rainfall of 1100 mm (NOAA, 2015). The site was characterized by a triassic underlying soil (HSG D; white store-urban land complex) of approximately 70% silt and clay with an average infiltration rate ranging from 0.00 to 1.50 mm/h (Soil Survey, 2015).

Four parking stalls (50 m^2 total area) were retrofitted with permeable interlocking concrete pavement (PICP) and designed to treat 15.2 m^2 of contributing impervious asphalt (0.3:1 run-on ratio) (Fig. 2). Its design followed typical hydrologic and structural standards for permeable pavement in North Carolina (NCDEQ, 2012). The PICP profile consisted of layers of crushed granite aggregate (Fig. 1): 375 mm of washed ASTM No. 2 aggregate subbase (nominal size 37.5–63 mm), 100 mm of washed ASTM No. 57 aggregate overlying the subbase (nominal size 4.75–25.0 mm), 50 mm of ASTM No. 78 aggregate (nominal size 2.36–12.5 mm), and 78 mm-thick concrete pavers with No. 78 stone filling their joints (ASTM D448, ASTM, 2012). To increase exfiltration, the site incorporated a 150-mm IWS zone. The subgrade was also ripped on 0.25-m centers, following Tyner et al.'s (2009) methods to improve exfiltration. The site was constructed in March 2014.

2.2. Monitoring and data collection

Hydrologic and water quality monitoring was done from March 2014 to April 2015. Rainfall was measured onsite using manual and 0.254-mm resolution tipping-bucket rain gauges affixed 1.8 m above the ground in locations free of overhanging trees or structures. ISCO 6712™ water quality samplers (Teledyne Isco, Lincoln, Nebraska) were installed to monitor hydrology and water quality from a reference site located within the same parking lot (38 m apart) and from the effluent

Fig. 2. From left to right: (a) aerial view of Piney Wood park: 50 m^2 of PICP (in red), 15.2 m^2 of contributing watershed area (in blue) and 1390 m^2 reference watershed (in yellow) with reference sampling location (black star) and effluent sampling location (white star); (b) Piney Wood PICP retrofit. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)