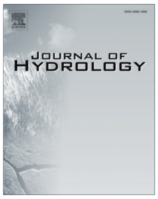
Journal of Hydrology 527 (2015) 923–932

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol



Retrofitting with innovative stormwater control measures: Hydrologic mitigation of impervious cover in the municipal right-of-way

Jonathan L. Page [a,*], Ryan J. Winston [a], Dave B. Mayes [b], Christy Perrin [c], William F. Hunt III [a]

[a] Department of Biological and Agricultural Engineering, North Carolina State University, Box 7625, Raleigh, NC 27695, United States
[b] Stormwater Services Department, City of Wilmington, 209 Coleman Road, Wilmington, NC 28412, United States
[c] Department of Agricultural and Resource Economics, North Carolina State University, Box 8109, Raleigh, NC 27695, United States

ARTICLE INFO

Article history:
Received 16 January 2014
Received in revised form 23 March 2015
Accepted 24 April 2015
Available online 3 June 2015
This manuscript was handled by Laurent Charlet, Editor-in-Chief, with the assistance of Michael Bruen, Associate Editor

Keywords:
Stormwater control measures
Urban runoff
Impervious cover
DCIA
Right-of-way
Green street

SUMMARY

Impervious Cover (IC) has been shown to increase runoff volumes, peak discharges and pollutant loads to streams, which leads to degraded water quality and biological integrity. Stormwater Control Measures (SCMs) have been developed to mitigate the hydrologic and water quality impacts of urban areas and IC. This paired watershed study evaluated the impacts of SCM retrofits on hydrology for a small urban drainage area. In February 2012, a bioretention cell (BRC) street retrofit, four permeable pavement parking stalls and a tree filter device were installed to control and treat residential street runoff in Wilmington, North Carolina, USA. In the SCM-Retrofit catchment, 52% of the directly connected impervious area (DCIA) and 69% of the total drainage area was retrofitted for potential hydrologic mitigation. Underlying soils in the study area were urban sands. Peak discharge significantly decreased by 28%, while lag times in the catchment remained unchanged. Runoff depth significantly decreased by 52%. When compared to the control catchment, runoff depths in the SCM-Retrofit catchment were significantly less for events with low hourly rainfall intensities (<2.7 mm/h), but significantly greater for events with high intensities (>7.4 mm/h). During post-retrofit monitoring, runoff thresholds in the SCM-Retrofit and control catchments were 5.2 mm and 3.5 mm, respectively. The SCM-Retrofit runoff coefficient decreased from 0.38 to 0.18 and was substantially less than other runoff coefficients reported in the literature for conventional residential development. This study illustrated how a limited number of SCM retrofits installed within the public right-of-way can mitigate some of the hydrologic impacts of existing residential development.

1. Introduction

1.1. Impacts of impervious cover on streams

Impervious Cover (IC) associated with urbanization leads to increases in stormwater runoff volumes and pollutant loads entering surface waters (Jennings and Jarnagin, 2002; Line and White, 2007). Due to channelization and piping of runoff in urban areas (Leopold, 1968; Leopold 1991; Booth et al., 2002), streams draining these catchments tend to exhibit high in-stream pollutant concentrations, flashy hydrographs (increased Q_P and decreased T_L), as well as channel and bank instability causing degraded ecological function; this condition has been referred to by Meyer et al. (2005) and Walsh et al. (2005a) as “urban stream syndrome”. IC greater than 10% negatively impacts streams and aquatic ecosystems, and IC greater 25% severely impacts their ecological function (CWP, 1998, 2003; Schueler et al., 2009). Recently, it has been suggested that directly connected impervious area (DCIA) may be a better predictor of stream impairment and ecological degradation than total IC and focused efforts to decrease DCIA may result in heathier aquatic systems (Lee and Heaney, 2003; Hatt et al., 2004; Walsh et al., 2005b). DCIAs rapidly convey runoff to the watershed outlet and are the primary contributor of storm flow and pollutant load during small rainfall events (<25 mm) (Flint and Davis, 2007; Walsh et al., 2005b).

Abbreviations: ANOVA, analysis of variance; ANCOVA, analysis of covariance; BRC, bioretention cell; C_R, runoff coefficient; CWA, clean water act; DCIA, directly connected impervious area; IC, impervious cover; LID, low impact development; Q_P, peak discharge; RO_D, runoff depth; RO_T, runoff threshold; SCM, stormwater control measure; TIA, total impervious area; T_L, lag time; TMDL, total maximum daily load.

* Corresponding author. Tel.: +1 919 515 6771.

E-mail addresses: jlpage3@ncsu.edu (J.L. Page), rjwinsto@ncsu.edu (R.J. Winston), dave.mayes@wilmingtonnc.gov (D.B. Mayes), christy_perrin@ncsu.edu (C. Perrin), wfhunt@ncsu.edu (W.F. Hunt III).

http://dx.doi.org/10.1016/j.jhydrol.2015.04.046
0022-1694/

1.2. Decentralized Stormwater Control Measures (SCMs)

Utilizing decentralized, distributed stormwater controls and other green infrastructure components is one approach to decreasing DCIA (Booth and Jackson, 1997; Benedict and McMahon, 2002; Dietz, 2007). This approach can be implemented on privately and publicly owned lands during new urban development and as a retrofits to exiting development. SCMs include bioretention cells (BRCs) and permeable pavements; studies of these facilities have focused on individual systems or side-by-side comparisons to refine design guidance and regulatory standards (Brattebo and Booth, 2003; Brown and Hunt, 2011; Collins et al., 2008; Davis, 2008; Dietz, 2007; Luell et al., 2011; Rushton, 2001; Wardynski et al., 2012). For example, BRCs can maintain or restore pre-development hydrology by providing depressional storage and infiltration, which enhances ground water recharge and natural base flow to streams (Burns et al., 2012; Davis et al., 2009; DeBusk et al., 2011). Permeable pavements are well suited to mitigate the hydrologic impacts of urbanization through substantial reductions in peak discharge and runoff volume through storage of runoff within an aggregate base layer and infiltration into the underlying soil (Brattebo and Booth, 2003; Collins et al., 2008; Gilbert and Clausen, 2006; Fassman and Blackbourn, 2010).

1.3. Catchment-scale application of SCMs

Limited peer-reviewed literature is available on the hydrologic impacts of multiple SCMs installed as retrofits at the watershed or catchment-scale (Shuster and Rhea, 2013), though substantial data is available for newly constructed Low Impact Developments (LID) with distributed SCMs (Hood et al., 2007; Bedan and Clausen, 2009; Line et al., 2012; Wilson et al. 2014). At a residential LID site in Waterford, Connecticut, USA, with no DCIA, BRCs, grassed swales and permeable pavements effectively mitigated the hydrologic impacts of residential development (Bedan and Clausen, 2009; Hood et al., 2007). Runoff volumes and peak flow rates were 2.5 and 3 times less than an adjacent conventional residential development, respectively. In North Carolina, Line et al. (2012) reported a commercial LID watershed with undersized BRCs, permeable pavements and stormwater wetlands provided greater runoff volume reduction than a commercial watershed with a conventional wet detention pond. Wilson et al. (2014) similarly studied two commercial developments in North Carolina, where an LID site infiltrated nearly all (99%) of the annual runoff, and the adjacent conventional development with a large detention facility resulted in Q_P's 11-fold greater than the LID site. The Low Impact Developments examined by Bedan and Clausen (2009), Line et al. (2012) and Wilson et al. (2014) were all new construction. In the only published catchment-scale SCM retrofit field study known to date, Shuster and Rhea (2013) found that a voluntary and innovative incentive program was a successful vehicle for private parcel SCM implementation. In this study, 170 rain barrels and 83 rain gardens were installed in a 1.8 km^2 catchment. With a relatively small fraction the catchment retrofitted, a significant impact on select hydrologic metrics was detected. In a modeling exercise, Loperfido et al. (2014) showed that a catchment with distributed SCMs improved stream hydrology compared to a catchment with two centralized detention facilities; however, the distributed SCM catchment did not completely mimic a forested condition.

1.4. Purpose of study

Many streets and roadways are directly connected to the conventional storm sewer network through curb and gutter drainage systems. Transportation surfaces make up the majority of the impervious cover owned and maintained by municipalities. Historically, roadways have been designed to provide maximum traffic flow and adequate drainage to prevent flooding in the driving lane with little regard for control and treatment of runoff. Limited, but usable, space exists within the public right-of-way to install SCMs, which includes the street surface, sidewalk and plaza area. It is becoming increasingly important to quantify the impacts of retrofitting SCMs into existing development on runoff quantity as municipalities comply with watershed management or restoration plans and total maximum daily load (TMDL) requirements as outlined by the Clean Water Act (CWA). This study evaluated the hydrologic impacts of SCM retrofits constructed within the public right-of-way at a catchment-scale. The primary research objective was to determine whether or not a limited number of SCM retrofits can provide significant and appreciable hydrologic mitigation at the catchment outlet when the entire DCIA and contributing drainage area cannot be retrofitted.

2. Materials and methods

2.1. Site description

The study site is located in Wilmington, North Carolina, USA, a city in the state's southern coastal plain. Mean temperatures in summer and winter range from 23.9 °C to 27.2 °C and 7.7 °C to 12.7 °C, respectively. Normal annual rainfall at Wilmington International Airport (ID# 319457) is 1448 mm (State Climate Office of North Carolina, 2012). Two residential street catchments, a control and retrofit (SCM-Retrofit), were selected for this paired watershed study (Fig. 1). The control and SCM-Retrofit drainage areas were 0.35 ha and 0.53 ha, respectively. The straight-line distance between the catchments was 0.5 km.

Both catchments were medium-density residential areas with street surfaces, sidewalks, driveways, rooftops and open space; they were serviced by conventional curb and gutter drainage systems. Control and SCM-Retrofit housing densities were 25.7 homes/ha and 28.3 homes/ha, respectively. Total IC was the same in each catchment (60%) (Table 1). However, DCIA (street surface) in the SCM-Retrofit catchment was 24%, compared to 16% in the control.

The New Hanover County soil survey indicates underlying soils in the control and SCM-Retrofit catchments are Baymeade Urban and Leon Urban, respectively (NRCS, 2002). Particle size analysis (PSA) using the hydrometer method (Gee and Bauder, 1986) confirmed the USDA texture classification for the underlying soils to be sand (Gee and Or, 2002). Infiltration rates in sandy urban soils range from 50 mm/h to 460 mm/h and are greatly impacted by compaction (Pitt et al., 2008). Maximum longitudinal slopes in the control and SCM-Retrofit catchments were similar at 0.7% and 0.5%, respectively.

2.2. SCM retrofits

SCMs were constructed in February 2012 and included a BRC in-street retrofit, four permeable pavement parking spaces installed in two separate applications and one tree filter box installed along Dock Street and 12th Street (Figs. 2 and 3). Post-retrofit, TIA decreased from 60% to 58% and DCIA was cut in half, from 24% to 12% (Table 2). The BRCs extend 1.8 m into the existing roadway to create 3.5 m driving lanes (east and west bound). BRC media depth was 60 cm and comprised of 5% gravel, 87% sand and 8% fines (by volume); organic material used in the media was shredded pine bark (3% by weight). The BRCs were planted with native grasses, upland woody plants and shrubs. Four permeable pavement parking stalls 7 m × 2.4 m each were constructed in two separate sections on 12th Street. Permeable