12-5-2014

Evaluating Management Strategies for Urban Stormwater Runoff

Corinna M. Fleischmann
University of Connecticut - Storrs, corinna.m.fleischmann@uscga.edu

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Corinna Marie Fleischmann, Ph.D.

University of Connecticut, 2014

ABSTRACT

Urban stormwater runoff, a leading cause of waterway impairment, has become a focal point of urban stormwater management strategies. As urbanization increases, regulations demanding preservation of pre-development peak flow rates or runoff volumes have been implemented and low impact development (LID) is encouraged as a strategy to achieve this stormwater runoff reduction requirement. While the success of LID has been proven at the site-scale, limited watershed-scale assessment of LID has been conducted. This research explores the potential benefit of watershed-scale LID implementation on two common urban stormwater issues: degraded stream health and combined sewer overflows (CSOs). Assessment results indicate that both stream health and CSO volume reduction are possible for the 1-yr storm event if the percent impervious cover (%IC) can be reduced by 20%. Since a reduction of 20%IC is lofty in a dense urban setting, the practical extent of LID implementation in an existing urban watershed is scrutinized to determine if, based on the constraints of the built environment, LID should be realistically considered by watershed management. In a dense urban environment with typical constraints – requirement to maintain traffic flow, preexisting utility location, public vs. privately owned land, etc. – a 20% IC reduction is unreasonable using one stormwater management best management practice (BMP). To achieve maximum stormwater runoff reduction potential, an integrated, watershed-scale stormwater management approach is encouraged. The results of this

study assist watershed managers with decisions about the inclusion of LID while striving to achieve federal stormwater mandates concerning stormwater runoff.

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for Urban Stormwater Runoff

Corinna M. Fleischmann, P.E.

B.S. United States Coast Guard Academy, 1998
M.S.C.E. University of Texas, Austin, 2004

A Dissertation
Submitted in Partial Fulfillment of the
Requirements for the Degree of
Doctor of Philosophy
at the
University of Connecticut
2014

APPROVAL PAGE

Doctor of Philosophy Dissertation

Evaluating Management Strategies for Urban Stormwater Runoff

Presented by

Corinna Marie Fleischmann, B.S., M.S.C.E., P.E.

Major Advisor ____

Joseph T. Bushey

Associate Advisor ____

Michael E. Dietz

Associate Advisor ____

John C. Clausen

Associate Advisor ____

Timothy M. Vadas

Associate Advisor ____

Mitchell Heinemann

University of Connecticut

2014

ACKNOWLEDGEMENTS

"There is no growth in the comfort zone and no comfort in the growth zone"
-CAPT Andrea Marcille, USGC (retired)
Former Director of the USCG Leadership Development Center

When I began this process in August of 2009, I understood that, by design, this would be a rigorous academic process. I understood I would be challenged and that from that challenge I would grow. When I began this journey, I had no idea what life had in store for me. During the past five years, I have faced the greatest joy in my life – the birth of my two daughters – and a low that I plan to never revisit. I have been very uncomfortable and from that, have grown immensely. Without the support, patience and guidance of the following people, this study would never have been completed. So, to the following, with deepest gratitude, I say "thank you".

- First and foremost, I am forever grateful to the United States Coast Guard for providing me the opportunity and the financial support to return to school and gain this experience.
- My advisor, Dr. Joseph Bushey who despite the many academic, professional and personal commitments you have faced over the past five years remained my advisor. Your guidance and insight have been invaluable.
- My committee – Dr. Jack Clausen, Dr. Mike Dietz, Dr. Tim Vadas and Mr. Mitch Heineman. Thank you for your commitment to me and your assistance throughout this process. I know that I would not be at this point without you.
- My Coast Guard Supervisors during this period – Dr. Sharon Zelmanowitz, CAPT Chip Hatfield, CAPT Jonathan Russell and Dr. Hudson Jackson. When I tell other that the Coast Guard is an amazing organization that I will remain a part of for as long as I can, I know that the Coast Guard is only the umbrella. Each of you has played an important role to me over the last few years. Thank you for your collective ear and professional guidance through this process.
- My husband, Dana Fleischmann. I don't think you really understand how special your love, support and friendship is to me. There is absolutely no way that this could have been accomplished without you. I am forever thankful for our team!
- My parents, Susan and John Kellicut, who have always supported, encouraged and believed in me. Despite our physical distance, I know you are both right here.
- My girls, Josslyn and Jayna Fleischmann, who were both born during this dissertation process and who spent many hours at daycare or with sitters to allow me to focus. Thank you both of helping me maintain perspective and smile.
- My friends and colleagues – specifically CAPT Andrea Marcille, LCDR Mark Braxton, LCDR Aurora Fleming, and LCDR Meghan Steinhaus – thank you for always being there and supplying a judge-free zone. After ignoring everyone for five years, I am blessed to still have you all in my life.

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INTRODUCTION

As individual and governmental efforts seek to reduce the time and expense consumed by commuting/transportation and search for ways to improve employment, education and housing opportunities, urbanization is increasing (UN, 1995; Tisdale, 1942). Urbanization is a pervasive and rapidly growing form of land use change that disrupts a watershed's hydrological characteristics (USEPA, 2011(a), Grimm et al., 2008). The process of urbanization alters the natural landscape by increasing impervious cover (IC) and therefore decreasing stormwater infiltration and increasing stormwater runoff (Dietz, 2007; Brabec et al., 2002; USEPA, 1997). Additionally, urbanization stresses the natural system by fundamentally altering both biotic and abiotic ecosystem properties (Booth et al., 2004; Paul and Meyer, 2001). The environmental challenges that arise as a consequence of urbanization are not simple and there is not a well-defined solution (Booth et al., 2004). Amplifying the present issue is the US Census Bureau's (2012) prediction that by the year 2030 more than 60% of the world's population will live in an urban area. Predicted future expansion of urban centers further exacerbates the challenges of ecosystem alterations and increases the need for a solution that will reduce anthropogenic induced stress on impacted systems.

The impacts of urbanization on the natural hydrologic cycle have been well documented (USEPA, 2011(a); Bellucci et al., 2008; Walsh et al., 2005(a); Schueler, 2004). Increased building, roadway and parking lot densities associated with urbanization result in an expansion of impervious cover in urban watersheds. For this reason, impervious cover is often used as an indicator of the intensity of the urban environment (Brabec et al., 2002; Paul and Meyer, 2001; Arnold and Gibbons, 1996). As the percentage of impervious cover (IC) increases due to

urbanization, stormwater runoff, along with a host of pollutants associated with urban impervious surfaces, increases (Dietz, 2007; Brabec et al., 2002; USEPA, 1997).

Due to the fact that stormwater runoff from the built environment remains a leading cause of impairment in the nation's waterways, stormwater runoff has been the focal point of numerous studies (Garrison and Hobbs, 2011; Dietz, 2007; USEPA, 2002(a); Lee and Bang, 2000). The analysis of runoff in response to land use changes, the prediction of runoff for future climatic and land use conditions, and the study of the spatial variability of urbanization and its effect on runoff generation have all been studied (Olivera and DeFee, 2007; Bari et al., 2005; Tang et al., 2005; Burns et al., 2005; Kim et al., 2002; Brown, 1988). Recently, stormwater managers have become increasingly aware of the drastic alterations that traditional stormwater management has on the urban hydrologic cycle – minimizing infiltration to groundwater and enhancing runoff via impervious surfaces (Paul and Meyer, 2001; Arnold and Gibbons, 1996).

Historically, the primary goal of stormwater management aimed to rapidly collect and deliver surface runoff from developed lands to streams, lakes and rivers (Seybert, 2006; Brabec, 2002). This approach alleviated urban flooding and transported water away from areas of human habitation where it could cause illness/disease or disrupt the operation of urban services (Butler and Parkinson, 1997). In the 1990's, stormwater was classified as a significant source of pollution and the goals of stormwater management shifted toward the protection of the natural water cycle and ecological systems through the introduction of local source control, flow attenuation and treatment in naturally constructed biological systems such as ponds and wetlands (Niemezynowicz, 1999). Management realized, at this time, that the challenges they faced regarding the urban hydrological cycle were a result of increases in IC. Reduced infiltration, reduced groundwater recharge and changes in the pattern of surface and river runoff that

imposed high peak flows, large runoff volumes and accelerated transport of pollutants and sediment from urban areas were all a result of increases in IC (Niemezynowicz, 1999).

Since the 1990's a variety of stormwater handling and treatment methods have been developed based on the idea that stormwater should be attenuated locally (Martin et al., 2007). Modern stormwater management practices consider a combination of structural (those strategies focusing on physical interventions and investments in engineered infrastructure for improved drainage) and non-structural strategies (preventive actions and behavioral changes) to achieve an integrated stormwater management approach (Parkinson, 2003). Many of these modern management practices are based on small-scale, environmentally sound technologies that involve natural or constructed biological systems for stormwater treatment (Niemezynowicz, 1999). These decentralized stormwater management practices encourage rainfall capture, improve infiltration, reduce stormwater runoff and improve the health of surrounding waterways (USEPA, 2007(b)). Stormwater management practices of this nature are commonly referred to as green infrastructure. Green infrastructure is a stormwater management approach focusing on maintaining healthy waters using natural processes and is designed to capture the first inch of rainfall resulting in the capture of approximately 80 to 85% of the precipitation events (Medina et al., 2011; USEPA, 2007(a)). Low impact development (LID) is one type of green infrastructure that specifically emphasizes better management of urban stormwater through reductions in post-development runoff by increasing on-site infiltration and reducing impervious surface cover (Pitt and Clark, 2008; USEPA, 2007(a); Sample and Heaney, 2006).

Across the nation, there is increasing interest in the use of LID as a means of reducing urban runoff and associated pollutant loads to receiving waters (USEPA, 2012(a), USEPA, 2011(a), Dietz and Clausen, 2008; Khader and Montalto, 2008). As awareness for the need to

improve water quality increases, LID is being implemented with the intent of providing practical solutions to diffuse pollution problems (D'Arcy and Frost, 2001). The use of LID to manage and treat urban stormwater runoff has become a common alternative practice to conventional solutions in urban watershed management (USEPA, 2004(a)). U.S. cities, like Philadelphia and Milwaukee, have implemented LID technologies as a part of their stormwater management plans (Philadelphia, 2011; Fresh Coast, 2011). The U.S. Environmental Protection Agency (EPA) considers LID a stormwater control best management practice (BMP) and, along with other federal agencies, is encouraging the implementation of LID (USEPA, 2012(b); USEPA, 2007(a)). While the stormwater BMP concept encompasses a wide variety of technologies and activities intended to minimize the effect of watershed development on flow regimes, LID technologies specifically fall under the umbrella of stormwater management BMPs (Perez-Pedini et al., 2005). Various LID BMPs (e.g., bioswales, bioretention basins, porous pavement, tree boxes, rain barrels) have been used in retrofitting existing development and in planning for new development to achieve improved hydrologic objectives (Lai et al., 2005; USEPA, 2000).

The implementation of stormwater management strategies occurs over multiple spatial scales, from site to neighborhood to watershed levels (Damodaram et al., 2010; Williams and Wise, 2006). Currently, a bottom-up, site level evaluation for implementation of these smaller scale management practices are performed and system-wide potential is evaluated by scaling-up unit specific predictions. While end of pipe solutions are the current approach to minimizing pollution, future sustainable urban water systems are best developed by elimination or control of pollution sources on site (Gray and Becker, 2002). Large-scale top-down approaches that maximize the utilization of limited resources by identifying sites that have the greatest potential for success are key for future success in the management of urban stormwater runoff (Petrucci et

al., 2012; Meierdiercks et al., 2010). By considering the placement of various management strategies at the watershed-level prior to actual implementation, resources will not be wasted on developing site-specific designs. Additionally, factors that may be beneficial at the site scale may inhibit implementation at the watershed level or vice versa. Studies at the catchment level support the idea that LID technologies that aim to regulate flow using site specific LID design elements can be ineffective and even harmful for some catchments (Petrucci et al., 2012; Fennessey et al., 2001). Evidence that runoff volume regulations can be effective for peak flow rate reduction at the catchment scale is still needed (Petrucci et al., 2012).

The evaluation and decision for implementation of LID at scales beyond the site level is critical as community and watershed-level land use management planning decisions are typically performed at the larger neighborhood or watershed scale (Grimm et al., 2008; Arnold and Gibbons, 1996). Additionally, the connection between small-scale individual LID performance and watershed-level LID implementation effectiveness is necessary to assess the potential for reduction in stormwater runoff, particularly given the inclusion of LID into recent EPA directives for stormwater and CSO management approaches (USEPA, 2010). Most previous LID implementation projects have encouraged site scale projects for the treatment of minimally-sized storms (Garrison and Hobbs, 2011; CNT, 2010; Gordon et al., 2010). Prior research efforts regarding the application of these LID site designs have been optimized relative to site-specific factors such as type, area, depth, and plants as well as investigated for the potential impact of site conditions such as weather, precipitation amount, soil type, and percent impervious area (Montalto et al. 2007; CICEET, 2007; Xiao, 2007; Dreelin et al., 2006). However, since the implementation of stormwater management strategies occurs over multiple spatial scales, design factors and challenges differ for watershed-level LID implementation relative to concerns at the

site level (Petrucci et al., 2012, USEPA, 2010). The distribution of LID within the implementable area, local hydrology, watershed topography, and the layout and type of existing impervious area are key factors that must be considered.

While stormwater regulations are shifting to incorporate IC reducing management practices, the management strategies applied to urban water systems can vary drastically by region (Bahir, 2012; USEPA, 2012(a)). Realistic estimates of the ability of LID to reduce stormwater in urban retrofits at the neighborhood scale are lacking (Petrucci et al., 2012, Meierdiercks et al., 2010). The EPA has recognized the need for watershed-level assessments of LID benefits and the identification of strategic locations for BMP implementation in urban watersheds (Lai et al., 2005). In April of 2011, the EPA released *A Strategic Agenda to Protect Waters and Build More Livable Communities through Green Infrastructure*. This document reaffirms the EPA's support of the use of green infrastructure to protect and restore waters and commits financial awards to selected communities within the US where green infrastructure is used to address water quality concerns. With this financial backing, an increase in the number of large scale LID implementation projects is practical. However, limited watershed scale LID implementation evaluations regarding modeled flow reductions have been performed and even fewer studies across larger urban areas or higher runoff volumes have been conducted. Environmental stewardship, prudent engineering and fiscal responsibility all dictate further watershed-scale evaluation of urban stormwater runoff management strategies to optimize the spending of the EPA's funding.

Adding to the complexity of the issues surrounding urban stormwater is the fact that engineered stormwater systems are often combined with sanitary waste water systems in a combined sewer system (CSS) which intensifies the pollutant loading (Belling et al., 2002).

When CSSs were designed in the early 1900s, their goal was to reduce the piping network necessary for an urban center (Chocat, 1996). On the occasion that the CSS was overloaded, excess untreated stormwater and sanitary wastewater were drained directly to nearby surface waters through combined sewer overflows (CSOs) to alleviate overloading the CSS and to prevent sewer backups by maintaining manageable flows to the wastewater pollution control facility (WPCF). Today, with increased urbanization, CSSs are plagued by overflows during large storm events which directly correlate to the degradation of urban surface water quality (USEPA, 2004(b)). The delivery of toxins, pathogens, sediment, chemicals, metals, fecal coliform, oil, grease, pesticides, fertilizers and trash directly to urban streams results in an absolute connection between CSO pollution and negative impacts on human health (Belling et al., 2002). The impact of CSOs on the environment has become a concern and a reduction in the number of CSOs is being mandated (USEPA, 2009; MDC, 2007). Municipalities are now separating sewer systems and redesigning the CSSs (Larrate and Chanson, 2008; Soonthornnonda and Christensen, 2008).

Additionally, the increase in imperviousness and the previous implementation of hydraulically-efficient drainage systems in a typical urban environment have resulted in alterations in the hydrology and geomorphology of urban streams (Barco et al., 2008; Hatt et al., 2004; Paul and Meyer, 2001). These hydrological alterations include increased frequency and intensity of elevated stream flows, increased concentrations of contaminants, decreased groundwater levels, and morphological changes to the stream including increases in both stream channel incision and bank erosion (Cuo et al., 2008; Walsh et al., 2005(b); Hatt et al., 2004; Novotny and Olem, 1994). These consistently observed patterns of ecological degradation to stream conditions associated with developed areas has been coined the “urban stream syndrome”

(Walsh et al., 2005(a); Meyer et al., 2005) and is linked to reduced biotic richness (Meyer et al., 2005; Paul and Meyer, 2001). The onset of aquatic system degradation occurs at approximately 10% IC in most watersheds (Bellucci et al., 2008; Brabec et al., 2002; Booth and Jackson, 1997).

The myriad of changes presented to a watershed through the process of urbanization all create unique challenges that need to be considered when devising an urban stormwater improvement plan. While LID has been touted as a solution to urban stormwater runoff (USEPA, 2012(a); USEPA, 2011(a); USEPA, 2009), LID as a watershed scale stormwater management strategy has not been proven. The extent of urbanization and the increase in %IC in developed areas may not be amendable to LID as a stormwater management strategy at the watershed scale. Past management techniques in urban areas have resulted in the rise of ancillary issues including negative impacts to stream health - increased pollutant loading, increased flowrate and decreased abundance in aquatic life (Roznowski and Roesner, 2010; Booth and Jackson, 1997; Poff et al., 1997), a rise in CSOs in cities with CSSs (Paul and Meyer, 2001), and a reduction in groundwater recharge (Roy and Shuster, 2009; Cuo et al., 2008). Additionally, the interactions of the sewer system with the WPCF and receiving waters must be considered when assessing the effectiveness of LID as a stormwater management strategy in an urban setting (Welker et al., 1999; Booth and Jackson, 1997). Since CSOs, WPCF outfalls, and stormwater runoff outfalls are all regulated differently, accounting for the impact of a management strategy on each component of the watershed is critical in evaluating effectiveness and in developing a management strategy.

Focusing on urban watersheds, the potential benefits of watershed scale reduction in IC as a management strategy in terms of stream health and alleviating CSOs is assessed. Furthermore, the matter of location and the feasibility of scale of implementation are also addressed. Through modeling, a determination of the ability of LID in an existing urban

watershed to reduce stormwater runoff volume to the degree necessary for watershed benefit is established.

Hypothesis

To address the gap between the proven success of LID at the site-specific level and the watershed approach necessary for urban stormwater management decisions, a modeling assessment of the effectiveness of LID in terms of stormwater runoff reduction at the watershed scale in an existing urban watershed was performed. The focus of this study was the Park River watershed in Hartford, CT, a representative urban watershed. In the Park River watershed, urban development has altered the natural connectivity of the watershed and the waterways are considered impaired (Fuss and O'Neill, 2010). This research investigates the potential of LID as a stormwater management strategy through an analysis of the feasible reduction of runoff volume during storm events in an existing watershed. Specifically, this assessment defines the practical role of LID, modeled as impervious cover reduction, in an urban stormwater management plan considering CSOs, urban streams, and the placement of LID in an existing urban neighborhood through specific research objectives. The hypothesis driving the proposed research is that *better descriptive data concerning the effectiveness of utilizing low impact development as a stormwater runoff best management practice in an existing urban watershed will improve the ability of watershed managers to make informed decisions that align with federal stormwater mandates concerning stormwater runoff volume reduction.*

Research Objectives

The above stated hypothesis was evaluated through the following specific objectives:

1. Investigate the potential of LID as a significant component of an urban stream improvement plan within existing urban watersheds,
2. Determine the potential for LID to alleviate CSOs and for targeting specific CSO locations for mitigation,
3. Address the gap between stormwater management decisions and LID design with respect to LID scale and location at the neighborhood scale under the constraints of space, cost, and transportation infrastructure.

The results obtained from this study provide useful information about the application of LID as a stormwater management strategy in existing urban watersheds. Current management strategies that use a “bottom-up” site-level evaluation rather than a “top-down” watershed approach lack the “big picture” required to maximize the benefit of LID implementation. This research presents valuable information to watershed personnel tasked with implementing stormwater management strategies. Furthermore, this research contributes to evaluating the tradeoffs between sewage and stormwater loads to waterbodies during CSS separation – a technique commonly employed to address sewage overflows. Current management approaches do not promote the simultaneous implementation of LID during CSS separation to reduce the resultant stormwater hydrologic and pollutant loads to receiving waters. Effective management of urban stormwater in such CSS areas is complicated by multiple regulatory agencies and approaches, often ignoring the potential for simultaneous sewage reduction and stormwater mitigation.

BACKGROUND

Study Area

My research focuses on the Park River watershed (Figure 1), an urbanized watershed of approximately 200 km^2 located within the Connecticut River basin. The watershed includes the Connecticut Towns of Avon, Bloomfield, Farmington, Hartford, New Britain, Newington, West Hartford and Wethersfield and is comprised of two primary sub watersheds, the North Park River and the South Park River (Fuss and O'Neill, 2010). As a means of flood control for the city of Hartford, both North and South branches of the Park River have channelized sections near their confluence that carry their flows separately to a twin-barreled conduit that discharges the main branch of the Park River to the Connecticut River. While flood control projects implemented over the last century have protected the City of Hartford from the type of catastrophic floods that occurred in the 1930s and 1950s, channelization and burial of portions of the Park River have dramatically altered the physical characteristics and habitat of the river (Fuss and O'Neill, 2010).

Additionally, land development patterns within the watershed and along the river have also contributed to the physical and biological degradation of the river. The current sewerage system consists of a CSS implemented in the 19^{th} century that includes 82 CSO locations, which during high flow events can deliver raw sewage into the Connecticut River and its tributaries (MDC, 2006). Urbanization has disconnected the river from the surrounding communities and has contributed to the deteriorated water quality and degraded habitat conditions in and along the river (CTDEEP, 2011) and, thus, has impacted the water quality of receiving water bodies.

Land use in the watershed ranges from heavily urbanized in the eastern and southern sections to undeveloped in the northern and far western portions. The dense urban development

of Hartford and West Hartford contribute most to the high imperviousness present in the eastern and southern portions of the watershed (Fuss and O'Neill, 2010). The average %IC for the Park River watershed is 54.9% but varies significantly by location of the subcatchment within the watershed from a low of 0% IC to a maximum of 100%IC. The median %IC cover value in the Park River Watershed is 59.7%. Generally, impervious area within the watershed consists of transportation infrastructure (parking lots, driveways, roadways) and roof tops.

The Park River watershed falls in the Central Valley geologic region, which is composed of Brownstone and Traprock overlain by glacial till (CTDEEP, 2010). Soils throughout all 3,351 catchments have been classified as moderately well-drained sandy and silty loam soils (USDA, 1986). However, while the base soil is suitable for infiltration and the installation of LID measures, surface soils have been heavily modified, representative of an urban environment. Normal temperatures range from 30°C during summer to as low as -8°C during winter with annual average precipitation and snowfall of 1175 mm and 1250 mm, respectively, for the period 1981-2010 (NOAA, 2010).

Low Impact Development

LID is considered a natural approach to stormwater management with a primary focus on decreasing the %IC within the watershed thus promoting infiltration and decreasing surface runoff (Fuss and O'Neill, 2010). The goal of LID is to preserve and recreate the natural, predevelopment characteristics of a site as closely as possible, even after development, and/or reduce the impacts to an acceptable level by managing rainwater at its source instead of discharging it into conventional combined or separated sewer systems thereby minimizing the impact of developed areas and restoring the natural water movement within the watershed

(USEPA, 2010; Martin et al., 2007; Zimmer, et al., 2007; USEPA, 2004(a); Coffman, 2001). Those who implement LID are typically seeking to decrease peak flow discharges into storm drains and water bodies following precipitation events with the objective of mimicking the hydrologic regime that existed prior to development (USEPA, 2009).

While implemented LID site designs have demonstrated hydrologic benefits in urban settings, LID has not been proven for large scale, watershed-level implementation (Petrucci et al., 2012; Meierdiercks et al., 2010; Hager, 2003; Lehner et al. 1999). The typical design objective for a LID site design is to maintain predevelopment hydrology for frequent storm events; the 6-month to 2-yr, 24-hr storms (Medina et al., 2011; Fuss and O'Neill, 2011; Zimmer et al., 2007; CTDEP, 2004; Prince George's County, 1999). In the absence of comprehensive measurements on catchment scale effects of LID, research about this topic has been based on hydrologic modeling. Past modeling efforts have extrapolated small-scale known processes to predict large-scale effects (Petrucci et al., 2012). Two primary issues have been identified with the scaling up of LID technologies; (1) the goal of preserving the pre-development water balance is not achievable at the catchment scale through flow rate constraint (Petrucci et al., 2012) and (2) LID implementation aimed at preserving pre-development peak flow rate locally can actually worsen the peak flow rate at the catchment scale depending on catchment's timing characteristics (Emerson et al., 2005; Goff and Gentry, 2006; McCuen, 1979). In particular, flow rate constraints do not cope with reduced infiltration volumes due to imperviousness and distort downstream low flow regimes (Booth and Jackson, 1997; Fennessey et al., 2010). A study performed by Meierdiercks et al., 2010 analyzed ten years of runoff data to compare three catchments – one undeveloped, one developed with the adoption of flow-rated source control (SC) regulations and one developed without the adoption of flow-rated SC regulations. In terms

of hydrologic behavior, the catchment developed with SC is closer to the one without SC than to the one undeveloped. The primary issue with constraining flow rate locally in a watershed is that a local reduction of a hydrograph's peak flow can produce a catchment-scale increase due to superposition of the hydrograph peak (Petrucci, et al., 2012). Therefore, any alteration in the timing of a hydrograph must be taken into account when making stormwater management decisions.

Despite limited examples of watershed-scale LID implementation, LID continues to be encouraged as a stormwater reduction and treatment process under the umbrella of green infrastructure (USEPA, 2012(b); USEPA, 2007(a)). LID delivers multiple benefits beyond its ability to reduce stormwater runoff; the ecological, economic and social benefits of green infrastructure, specifically LID, have made it an increasingly popular strategy (CNT, 2010). The inclusion of green infrastructure can result in increased green space (USEPA, 2009), which encourages physical activity in the community and has been shown to contribute to the improved health of local residents (Giles-Corti et al., 2005). Proximity to green space also increases property values (CWP, 2010) by improving the aesthetics of a community (CNT, 2010). The long-term benefits to the environment associated with using green rather than grey infrastructure for stormwater management has also been established (Garrison and Hobbs 2011; USEPA, 2010; CNT, 2010). Overall, LID improves community livability (Garrison and Hobbs, 2011; Roseen et al., 2011) and adds value to urban communities.

Measurement of Impervious Cover

A key component of this research is that the implementation of LID does reduce IC in a watershed which results in a decrease in stormwater runoff volume. Total catchment

imperviousness has commonly been used as an indicator of hydrologic change brought about by urban disturbances (Roy and Shuster, 2009; Walsh et al., 2005; Brabec et al., 2002). Stormwater runoff volume and the amount of IC in a watershed have been positively correlated, however, the influence of impervious cover varies substantially with the permeability of the pervious parts of the catchment and with how much of the impervious area drains directly to streams through pipes rather than draining to the surrounding pervious land (Walsh et al., 2005; Booth et al., 2004; Brown, 1988)

While percent IC in a contributing watershed is a widely accepted parameter used to characterize the magnitude of urban development, past efforts to quantify the degree of development using the IC metric have not been consistent (Booth and Jackson, 1997). The most significant issue is the distinction between total impervious area (TIA) and effective impervious area (EIA). TIA is defined as the fraction of the watershed covered by constructed, non-infiltrating surfaces such as concrete, asphalt and buildings (Booth and Jackson, 1997). While EIA is defined as the impervious surfaces with direct hydraulic connection to the downstream drainage or stream system. Thus any part of the TIA that drains onto pervious surface is excluded from the measurement of EIA. The concept of EIA captures the hydrologic significance of imperviousness (Booth and Jackson, 1997).

To assess how this particular urban watershed responded to variations in IC reduction methods, the two extremes of IC reduction were assessed – complete removal of IC (TIA) and the re-routing of runoff to pervious cover without making any modifications to the pervious ground cover (EIA). Examining EIA and TIA at both the 10% and 30%IC reduction levels for selected storm events solidified the fact that the method of IC reduction is important when looking to maximize runoff reduction (Figure 2). At the 10%IC reduction level, for storm events

larger than the 5-yr storm, using an EIA reduction method produced more watershed runoff (68-MG more for the 25-yr storm and 36-MG more for the 5-yr storm). Similarly, for the 30%IC reduction level, the EIA method of IC reduction produced 225-MG more runoff than the TIA reduction method for the 25-yr storm and 98-MG more for the 5-yr storm event. For the smaller, 1-yr storm event, at 10% IC reduction, the TIA method created 20-MG more runoff than the EIA method did for the watershed. At the 30% IC reduction level for the 1-yr storm, minimal runoff was created for either method of IC reduction. These results indicate that for larger storm events a hard reduction in IC (TIA) is more effective than re-routing runoff to pervious cover (EIA). For the smaller storm events, the runoff volume being re-routed does not overwhelm the pervious area. Therefore, the EIA reduction method is more effective at reducing the stormwater runoff volume exiting the watershed.

From a planning and management perspective, IC conditions are typically expressed as a percentage of the total land area with target values given similarly (TIA) rather than as a fraction of the initial value (EIA; Schueler, 1994). For most of this assessment, a "hard" reduction, the TIA method of reduction, was selected to mimic standard planning practice and because the previously mentioned hydrologic assessment of the watershed indicated that for larger storms a TIA method of reduction is more effective than re-routing runoff to pervious cover (EIA) in terms of reducing total watershed runoff. Since both large and small storm events were included in this assessment, a decision was made to utilize a TIA method of reduction across all the storm events for continuity of the results. The TIA "hard" reduction represents a direct subtraction of the %IC from the initial %IC rather than a percentage reduction of the initial value. In an urban watershed, the potential reduction in %IC is limited by the built environment. In this particular watershed, reducing the %IC by more than 30% would be difficult and very costly without major

overhauls on the infrastructure, which is not plausible (Hazen and Sawyer, 2012; USEPA, 2011(b)).

Stormwater Management Model (SWMM)

SWMM is widely used throughout the world for planning, analysis and design of stormwater runoff, combined sewers, sanitary sewers and other drainage systems (Rossman, 2010). For this assessment, the latest version of SWMM (version 5.0.022, released in April 2011) which simulates hydrology, hydraulics and water quality of urbanized watersheds was used (USEPA, 2011(b)). SWMM is a dynamic rainfall-runoff and hydraulic simulation engine that was designed to predict the resultant runoff in urban areas from each modeled subcatchment in response to precipitation input (USEPA, 2011(b)). The hydrologic processes modeled include precipitation, evaporation, surface runoff, infiltration, and groundwater flow. Both single event and continuous simulations can be preformed accounting for spatial and temporal variability in the climate, soil, land use and topography of the watershed (Muleta, 2012). Each subcatchment is parameterized by percent pervious/impervious, average slope, storage and infiltration. From these parameters, SWMM estimates a quantity of surface runoff relative to infiltration in response to a rain event using the non-linear reservoir method where surface runoff occurs only when the depth of the overland flow exceeds the maximum surface storage provided by ponding, surface wetting and interception, in which case the runoff is calculated using Manning's equation (Muleta, 2012). Horton, Green-Ampt and the Curve Number methods are all available to model infiltration. For this model, the Green-Ampt method was selected; parameters that govern the Green-Ampt method are the hydraulic conductivity, the soil suction head and the difference between moisture content and porosity (Sample and Heaney, 2006).

In addition to watershed runoff/infiltration, SWMM can incorporate engineered stormwater infrastructure (e.g., stormwater pipes, catch basins) to obtain a realistic understanding of the quantity and fate of urban stormwater. The runoff quantity and quality simulated from a watershed and the wastewater loads assigned to the receiving nodes are added and transported using either steady, kinematic wave or dynamic wave routing through a conveyance system of pipes, channels, storage/treatment devices, pumps, and hydraulic regulators such as weirs, orifices and other outlet types. Hydraulic conditions of any level of complexity including those experiencing backwater effect, flow reversal and pressurized flow can be accommodated (Muleta, 2012).

SWMM was selected for this assessment as: (1) an existing, verified model of the area of interest was available (Heineman et al., 2010) and (2) Version 5.0.022 has the ability to model various LID features including bioretention basins, porous pavement, vegetative swales and rain barrels. The 3351 catchment, validated Park River sewershed SWMM model also includes groundwater contributions to streams and the piping network as well as non-linear reservoir runoff for combined and storm catchments and unit hydrographs (RTK) for sanitary sewers outside Hartford. The average catchment size for this model is 22.40 acres with a median catchment size of 2.41 acres indicative of the fact that this particular model was designed to focus modeling efforts on the sanitary sewer system in the urban areas. In the more urbanized areas, the catchments are smaller and contribute to the modeled sewer system. The less urban areas, where a sewer system does not exist, are modeled as larger hydrologic catchments based on stormwater runoff. The model is calibrated and validated to numerous data sets including 27 installed flow meters at locations throughout the combined, sanitary and stormwater systems, 80 CSO regulators with data sets beginning in 2002 and 60 years of monthly observations by USGS

at a water table well at a location within the modeled area (Heineman et al., 2010). As LID improvements aim to enhance infiltration, the potential feedback to the engineered system via contributions from all watershed sources, including groundwater, needs to be considered.

In SWMM, LID can be generically modeled by altering the %IC of each subcatchment or specifically modeled by updating model subcatchment data to include specific LID designs. The resultant runoff reduction relative to the base case (no LID) can then be calculated for various LID coverages in the watershed using either the specific or generic modeling technique. Using the specific modeling technique, LID types can be modeled using the five modeling process layers available: the surface layer, the pavement layer, the soil layer, the storage layer and the underdrain layer. The surface layer corresponds to the ground surface that receives direct rainfall and run-on from up-gradient land areas, stores excess inflow in depression storage and generates surface outflow that, in this case, flows onto down-gradient land areas. The pavement layer provides specifics about the characteristics of the particular pavement mix and is used solely when modeling porous pavement. The soil layer is the engineered soil mixture used in bioretention cells to support vegetative growth. The storage layer is a bed of crushed rock or gravel that provides hydrologic storage. The underdrain system conveys water out of the storage layer into a common outlet pipe or chamber. All of the specific LID controls modeled in SWMM provide some amount of rainfall/runoff storage and evaporation of stored water with the exception of rain barrels (USEPA, 2011(b)).

The Park River Model

SWMM was chosen specifically for this research due to its ability to model continuous or single-event precipitation simulations and because an existing, verified model of the watershed

was available (Heineman, et al., 2010; Huber, 2003). While SWMM typically is used to model specific components of an urban stormwater system, very few models have addressed complete urban collection systems (Heineman, et al., 2010). An integrated Park River sewershed model was constructed, calibrated, and validated by Camp Dresser and McKee (Cambridge, MA) at the request of The Metropolitan District Commission in Hartford, CT. This particular model has 3351catchments that are used to assess hydrologic changes to urban streams as a result of stormwater runoff. Among urban watershed hydrologic models, the CDM SWMM model is unique in its inclusion of sewage, watershed runoff, and groundwater contributions to both the stream and the combined piping network. As reducing IC will enhance infiltration, the potential feedback to the engineered system via contributions from a rising groundwater table is significant (Crites and Tchobanoglous, 1998).

For this urban watershed, specific model parameters for modeling runoff transport and infiltration were utilized. The Green-Ampt method for modeling runoff relative to infiltration in response to a rain event was chosen. The Green-Ampt method for modeling infiltration assumes that a sharp wetting front exists in the soil column, separating soil with some initial moisture content below from saturated soil above (Rossman, 2010). Unlike Horton's Equation, which is based on empirical observations, requires maximum and minimum infiltration rates and is typically applicable only to events for which the rainfall intensity always exceeds the infiltration capacity, the Green-Ampt method is a physically based model which can give a good description of the infiltration process. Parameters that govern the Green-Ampt method are the hydraulic conductivity, the soil suction head and the difference between moisture content and porosity (USEPA, 2011; Sample and Heaney, 2006). For runoff transport, dynamic wave routing was selected. Flow routing within a conduit link in SWMM is governed by the conservation of mass

and momentum equations for gradually varied, unsteady flow and the user has a choice of steady flow routing, kinematic wave routing or dynamic wave routing (Rossman, 2010). The dynamic wave routing solution method produces the most theoretically accurate results because the equations used consist of the continuity and momentum equations for conduits and a volume continuity equation at the nodes within SWMM (Rossman, 2010).

The CDM SWMM model is calibrated and validated to numerous datasets including flow meters at 27 locations throughout the combined, sanitary and stormwater systems. These data are supplemented by depths measured continuously at 80 CSO regulators, long-term continuous flows at the Water Pollution Control Facility (WPCF), 12 permanent flow meters at Hartford's borders installed in 2008, detailed flow metering in the outlying communities from 2005 and 2009, daily flow records on eight streams collected by USGS between 1936 and 1986, and 60 years of monthly observations by USGS at a water table well in a nearby town (Heineman et al., 2010). For this particular model, the baseline, or 0%IC reduction, scenario uses actual 2006 land cover conditions as an input file.

METHODOLOGY

Data

Precipitation data – Storm event data was selected from existing historical precipitation records or created based on design storm guidelines developed by Miller et al. (2002). An hourly precipitation data file in National Climatic Data Center (NCDC) format collected at Bradley International Airport in Windsor Locks, CT from 1954 to 2009 was used to select historical storms for this assessment. The airport is located approximately 13.7 km north of the study area. More recent storm data, 2009 to present, was created in NCDC format for consistency with the

original rainfall data. This more recent precipitation data was obtained from the NCDC (*http://gis.ncdc.noaa.gov*).

For each %IC reduction scenario in each evaluation, several storms were assessed. Using Miller et al. (2002), Department of Commerce (1961), Connecticut Stormwater Quality Manual (CT DEEP, 2004), and MDC (2004), the 3-month, 1-yr, 2-yr, 5-yr, 10-yr and 25-yr, storm events were either created for the Park River Watershed or selected based on historical data. All storms chosen for assessment were verified using local IDF curves (Miller et al., 2002). For the engineering evaluation of runoff reduction, design storms were prepared base on respective return periods for Connecticut Region II using Miller et al. (2002).

Since typical stormwater treatment practices and LID designs are designed to retain the volume of runoff generated by 1-inch of rainfall, the 1-yr storm event– which, in this area, produces 1-inch of rainfall - was the typical storm event evaluated for this research (Medina et al., 2011; Garrison and Hobbs, 2011; CT DEEP, 2004; Prince George's County, 1999). The smaller, more frequent storm events account for the majority of runoff volume and are therefore necessary for assessment (Pitt and Clark, 2008). As the ultimate goal of this investigation is determine whether or not LID implementation can be effective in this urban watershed, a variety of larger, potentially hydrologically disruptive precipitation events were also reviewed. The larger, less frequent rain events are also necessary in this assessment as their rainfall volume will challenge LID's ability to reduce runoff quantity (Pitt and Clark, 2008).

<u>*Land cover data*</u> – The SWMM model created by CDM was created in 2009 and used the most recent land cover data set at that time; the 2006 land cover data for Connecticut (CLEAR, 2012). Land cover, as its name implies, shows the "covering" of the landscape. This is to be

distinguished from land use, which is what is permitted, practiced or intended for a given area. Land cover information comes from remotely sensed data from satellites. Sensors aboard the satellite collect (sense) radiation in a number of different wavelengths that is reflected from the surface of the earth. The data are converted via computer programs and human expertise into land cover maps made up of many pixels of information that are 30 meters (or about 100 feet) square (CLEAR, 2012).

Modeling LID as IC reduction in SWMM

For the assessment of each objective, the Park River model subcatchment data was updated to incorporate a specified reduction in %IC ranging from 0% IC reduction to 100% IC reduction. For this model, the 0%IC reduction case is referred to as the baseline case. The baseline case uses the 2006 land cover conditions mentioned previously as an input file. For the 5% through 30% IC reduction cases, the %IC for each catchment within the model was either reduced by a “hard” reduction (TIA method) – a direct subtraction of the %IC of the initial %IC listed in that particular catchment in SWMM – or reduced by the EIA method – where the % routed to a pervious surface was increased for each subcatchment. In each case, if the %IC reduction called for by the particular case was greater than the initial %IC value for the subcatchment then the %IC was set to zero. By allowing the %IC for a particular subcatchment to be zero, the assumption is made that it is possible for all IC to either be removed or completely offset by green infrastructure. The final cases assessed, the 100% IC reduction scenario, aims to mimic the watershed as it existed prior to anthropogenic influence. For the 100% IC reduction scenario, %IC in each subcatchment was set to zero and sewer piping was removed from the model.

To mimic LID implementation, model simulations across a range of storm sizes and %IC reductions are evaluated to demonstrate the impact of LID on stormwater capture and conversely runoff in this urban watershed. For each objective, IC reduction scenarios were used to calculate the reduction in runoff relative to the baseline case. All initial runs were modeled using a 1-yr, 24-hr storm event (Type III) as required by typical LID design standards (ex: Medina et al., 2011; MEDEP Stormwater Management Manual; INSUIT, 2009; CTDEP, 2004; Prince George's County, 1999; Lehner et al., 1999). This method of LID implementation allows a generic LID evaluation to be conducted for this watershed.

Modeling specific LID technologies in SWMM

For Objective 3, specific LID technologies will be modeled in SWMM. All LID designs were developed in accordance with published guidelines and accommodate the rainfall volume of a 10-yr, 24-hr storm and the high intensity rainfall created by a 1-yr, 30-min storm (CTDEP, 2004). The available implementable width of each individual LID technology will be determined by the width of the narrowest roadway considered and the AASHTO requirement of 6.1 m (10 ft) of paved roadway for one traffic lane and one parking lane (AASHTO, 2004). It was assumed that the grass buffer between the edge of the road and the sidewalk could be included when necessary and that the length available for implementation of roadway LID features is restricted by existing driveways. The final dimensions of each LID technology implemented were adjusted based on design standards. Each LID feature considered was identically sized throughout the watershed for consistency. Ignoring potential contributions from other areas, the paved roadway remaining after LID implementation was assumed to be the area captured and treated by the LID feature. The implementation of the LID technologies that do not interfere with existing roadway

were designed to correspond to the implementation distances used for the roadway LID technologies. The calculated design area for each LID feature was then entered into the appropriate catchments in SWMM.

General Methodology for each Objective

<u>Objective 1</u>: *Investigate the potential of LID as a significant component of an urban stream improvement plan within existing urban watersheds.*

The stream health portion of this research identifies the extent of the hydrological restoration to urban streams that can be achieved by decreasing IC in an existing urban watershed. Examining the effect of a watershed-wide reduction in %IC on stream hydrology provides valuable insight to watershed decision makers with limited resources to allocate when developing management strategies. Using SWMM, the effect of reducing IC, the typical stream health index, on watershed runoff was evaluated. The changes in magnitude of runoff, the reduction in peak flow and change in peak runoff timing were evaluated at twelve locations along the urban stream within the watershed. These twelve points were chosen to highlight the urban gradient present in the Park River Watershed and to correspond to sites in the watershed where field data had been collected. This evaluation was performed for created 1-yr, 2-yr, 5-yr, 10-yr and 25-yr, storm events to encompass the range of storm events that would challenge a LID design. To fully describe the potential variability for the LID design storm event, the 1-yr storm, variations in the intensity of the created storm were also analyzed. In addition to the 24-hr storm intensity, the 1-hr and 6-hr storm intensities were also assessed for each %IC scenario up to the 30% reduction condition for the 1-yr storm.

Objective 2: Determine the potential for LID to alleviate CSOs and for targeting specific CSO locations for mitigation.

The Park River SWMM model was utilized to assess the practicality of LID as a solution to alleviate CSOs as mandated in urban watersheds (USEPA, 2009; MDC, 2006). The potential to alleviate certain overflows through reduction in volume of stormwater runoff from each of the predetermined CSOs within the Park River Watershed was assessed. This assessment specifically investigates the potential of LID to be part of a CSO management plan, assesses the impact of storm size on CSO overflows, and examines the potential for targeting specific CSO locations for elimination.

The practical extent of the ability of LID to reduce stormwater runoff was assessed across a range of LID implementation levels. Six storm sizes (3-month, 1, 5, 10, 25 and 50-yr return periods) were evaluated to provide an estimate of the volume of runoff reduction possible for each %IC scenario for each storm size. For each simulation, the number of active CSOs was determined by counting those CSOs generating flow in the model for the given scenario. Each CSO was then evaluated and identified as: (1) never overflowing, (2) always overflowing, or (3) by the specific %IC reduction required to eliminate overflow as a function of storm size. This assessment was performed to examine the extent to which LID techniques, through stormwater runoff volume reduction, can assist in reducing the volume of CSOs and the number of CSO events. The resultant reductions in the CSO volumes and quantity will be used to provide direction for managing CSOs, particularly in this specific study area, Hartford, CT.

Objective 3: *Assess the gap between stormwater management decisions and LID design with respect to scale and location at the neighborhood scale under the constraints of space, cost, and transportation infrastructure.*

Several LID designs were assessed in an existing urban watershed to determine the practicality of LID implementation and greatest potential stormwater reduction given the constraints of the built environment. As in many urban watersheds, the potential area for LID is constrained by the existing neighborhood structure. A smaller sub-watershed of the Park River Watershed, the Granby Watershed, was examined for this evaluation due to the watershed's high IC. This assessment focuses on publicly-owned land since alterations involving private land require owner buy-in along with an assumed increase in cost and maintenance requirements for the homeowner. Most publically-owned land in this dense urban neighborhood is roadway. Therefore, the potential impact on traffic was considered when locating and sizing the LID features in the watershed. There is 24.4 km of roadway in this neighborhood resulting in a range of possible implementation distances from 0 km (0%) to 24.4 km (100%). To assess this range, eight implementation scenarios were evaluated for each LID technology and compared to the baseline (no LID/0 km) case. Street selection for implementation was evenly distributed throughout the watershed while accounting for transportation needs and LID implementation limitations. Due to public transportation corridors, and the primarily north-south traffic flow, street selection focused on east-west secondary roadways. As implementation coverage was increased, secondary east-west streets were selected followed by secondary north-south streets. The two primary transportation corridors on either side of the neighborhood were not selected until the 100% implementation scenario because transportation analysis indicated that including these primary commuter routes will adversely affect traffic flow and negatively impact public

transportation (Jackson et al., *in preparation*). All simulations were performed using a historical 1-yr storm event, the minimum design storm for most LID technologies (Medina et al., 2011; CTDEP, 2004).

Total runoff for the Granby watershed was assessed by summing the runoff from each of Granby's 119 subcatchments within SWMM. Results of each run were subsequently compared to the condition where no LID was implemented to determine a percent runoff reduction resulting from LID implementation. Six specific LID designs were implemented in the model at eight levels of coverage to assess the potential hydrological benefit of LID implementation. After all eight distance implementation scenarios were assessed for each LID feature using the 1-yr storm event, the cost benefit of each technology was considered through a comparison of implementation cost with runoff reduction potential. The LID feature that provided the greatest runoff reduction at the lowest cost in this watershed was then used to perform a sensitivity analysis on the placement of LID within the watershed. Five different location scenarios were evaluated to determine the effect of LID placement on runoff reduction. From a transportation perspective (Jackson et al., *in preparation*), a roadway coverage of 4 km (16% of the total roadway in the watershed) was deemed acceptable because roadway alteration at this distance does not negatively impact traffic flow. LID implementation scenarios were created following the pre-determined roadway restrictions and were therefore implemented on east-west streets. LID placement was evaluated at the (1) top, (2) middle top, (3) middle, (4) middle bottom and (5) bottom of the watershed to establish the ideal location for maximum runoff reduction.

The results of this assessment of the impact of LID type, cost and location on runoff reduction in this urban setting present results necessary to determine if utilizing LID as a stormwater management practice is practical in this urban setting. This approach highlights a

top-down watershed-level implementation evaluation and does not evaluate specific individual site feasibility. The focus of this assessment is the overall potential of LID for consideration in watershed management decisions to inform neighborhood-wide decisions of whether or not to include LID in a management plan and, if so, which technologies would best serve the community.

Modeling the effect of impervious cover reduction on watershed runoff and urban stream health

Submitted to Journal of Water Resources Planning and Management

ABSTRACT

Increasing impervious cover (IC) in urban areas alters stormwater hydrology and contributes to the degradation of urban stream health. Current stormwater management strategies emphasize the use of low impact development (LID) as a stormwater control measure. The effectiveness of watershed-wide installation of LID, or reduction in IC, on the hydrology of event-based stream flow metrics (total runoff, peak flow rate and time to peak) was examined at the watershed scale using a hydrologic sewershed model (SWMM). Initial average %IC of the subcatchments ranged from 6% to 43%. This assessment reveals that runoff volume reduction increases as %IC is reduced for all storm sizes; however, runoff cannot be eliminated at the watershed scale. Furthermore, an assessment of the effect of storm intensity on the evaluated hydrologic metrics illustrates that the greatest peak flow rate for the 1-yr storm was produced by the 1-yr, 6-hr storm event. Consequently, this 6-hr event allows for the greatest total runoff reduction as IC is reduced.

INTRODUCTION

Land use changes disrupt the hydrologic characteristics of watersheds resulting in changes to the magnitude, duration and frequency of stream flow as well as decreased infiltration (USEPA, 2011). In urban areas, hydrologic change is one of a complex array of potential stressors related to the amount of impervious cover (IC) that affect streams (e.g. altered hydrology, increased pollutant loading, temperature increases, and decreased habitat quality; Bellucci et al., 2008; Schueler, 2004). The consistently detected patterns of ecological degradation to stream conditions associated with urban land use are so common that they have been coined the “urban stream syndrome” (Walsh et al., 2005(b)), which includes flashier hydrographs and morphological changes of the stream. The quantity of IC in a watershed has commonly been used as an indicator of development on stream health (Bellucci et al., 2008; Walsh et al. 2005(a); Schueler, 2004; Arnold and Gibbons, 1996) and has been adopted as a metric of the aggregate negative effects of urbanization on stream health (Booth et al., 2004; Paul and Meyer, 2001; McMahon and Cuffney, 2000). Although the influence of total IC on stream hydrographs varies substantially with the permeability of watershed surfaces and the connectivity of impervious area to streams, research confirms aquatic system degradation occurs at approximately 10% IC (Bellucci et al., 2008; Walsh et al., 2005(b); Booth et al., 2004; CWP, 2003; Brabec et al., 2002; Booth and Jackson, 1997).

Hydrologic metrics that demonstrate altered stream flow regimes can provide a direct mechanistic link between aspects of urban development and degraded stream ecosystems (Booth et al., 2004). Flow has been demonstrated to be a major driver behind many processes that ultimately determine the health of a stream ecosystem (Egderly et al., 2006; Bunn and Arthington, 2002; Poff et al., 1997), including the distribution of the benthic macroinvertibrate

community. Research suggests that stream quality can be determined by analyzing benthic macroinvertebrate communities (Roznowski and Roesner, 2010; DeGasperi et al., 2009; Booth et al., 2004). Therefore, any metric used to assess the impact of urbanization on stream health must be sensitive to benthic communities, or an associated parameter such as peak flow rates, while measuring urban development (Roznowski and Roesner, 2010). Runoff volume, duration and peak flow rate are three metrics of a flow regime identified as important to stream geomorphology, and, thus, stream biota (Egderly et al., 2006; Poff et al., 1997).

Improving stream health is desirable in many urban watersheds where ecological degradation to stream conditions has been observed. To combat the negative impacts to streams associated with the 'urban stream syndrome,' watershed management strategies aimed at reducing peak flow rate and extending the hydrograph have been implemented (Finkenbine et al., 2000). Since the goal of watershed management is to restore or maintain the chemical, physical, and biological integrity of surface waters, state and local governments have made an effort to protect stream geomorphology through the implementation of laws aimed at restoring post-construction watersheds to their pre-construction hydrologic states (Tillinghast et al., 2010; CT DEP, 2002; IUCN, 2000). Until recently, the engineered approach to stormwater management was to remove water as quickly as possible through the curb and gutter approach (Seybert, 2006), resulting in increases in the magnitude of runoff, peak flow, and storm event frequency while decreasing stream peak duration as runoff travels quickly through the engineered systems and over impervious surfaces (Roznowski and Roesner, 2010; Booth and Jackson, 1997; Poff et al., 1997).

Low impact development (LID) has become an increasingly popular alternative relative to traditional curb and gutter approaches to stormwater management. Distributed LID measures

that intercept rainfall from small events and facilitate infiltration, evaporation, transpiration and/or storage have been suggested as a means to improve stream health (Walsh et al., 2005(a)). The objective of LID is to mimic predevelopment hydrologic site characteristics and minimize the impacts of development through reductions in effective IC that improve infiltration and decreases runoff (USEPA, 2010; USEPA, 2004). Using LID techniques, such as bioretention areas, grassed swales and porous pavement, decreases runoff as the watershed retains stormwater (Dietz and Clausen, 2008). However, hydrologic assessments of LID implementation at the watershed scale are limited (ex: Jordan Cove located in Waterford, CT; Bedan and Clausen, 2009) and no larger scale, urban watershed studies have specifically examined the potential impacts of LID implementation on the potential health metrics of urban streams. While effective for peak flowrate reduction, LID techniques may be limited in terms of the magnitude of infiltration possible due to the degree of IC relative to the flow rates produced in an urban landscape (Tillinghast et al., 2010). Additionally, the ecological benefit of managing an increased peak flow introduced by larger flooding events may be small (Walsh et al., 2005(b)). Examination of stormwater control measures at the site scale show that while specific Best Management Practices (BMPs) reduce the peak flow, the duration of elevated flow conditions lengthen and BMPs may actually be subjecting streams to longer periods of erosion if peak flows remain above threshold values (Roesner et al., 2001). Observations from Nehrke and Roesner (2004), Bledsoe (2002), Bledsoe and Watson (2001), and Roesner et al. (2001) have shown that stormwater control measures actually cause higher rates of erosion due to the increase in frequency and duration of the sub-bankfull flows. For this reason, the capability of LID as an effective management strategy requires further assessment.

The goal of this research is to examine the effect of reducing IC using event-based stream flow metrics to determine if the implementation of LID as a stormwater management technique has the potential to improve stream health in an urban watershed. Possible hydrological restoration was determined through assessment of the impact of IC reduction on runoff magnitude (Q_{total}) and the peak flow rate (Q_p) for various storm sizes. The chosen metrics were also assessed with regard to the impact of storm intensity and watershed pre-storm wetness condition. Through modeling, an analysis on the upper limit of LID effectiveness based on storm size and initial catchment IC was conducted. Examining the effect of a watershed-wide reduction in IC, on stream hydrology will provide watershed decision makers the insight necessary to develop holistic watershed management strategies.

STUDY AREA

The Park River watershed (Figure 3) was selected for investigation based on the degree and gradient of urbanization and the existence of a validated watershed model. The Park River watershed covers approximately 199-km^2 in Hartford, CT, with land use ranging from heavily urbanized in the eastern and southern sections to undeveloped land in the northwestern portion. The dense urban development of Hartford and the surrounding towns of Avon, Bloomfield, Farmington, Hartford, New Britain, Newington, West Hartford and Wethersfield contribute to the high imperviousness in the eastern and southern portions of the watershed (Fuss and O'Neill, 2010). The average %IC for the watershed is 54.9%, but varies by location within the watershed from a low of 0% IC in the northwest to a maximum of 100% IC in the southeast. Generally, impervious cover within the watershed consists of transportation infrastructure (parking lots, driveways, roadways) and roof tops.

The watershed is comprised of two subwatersheds, the North Park River and South Park River watersheds (Figure 3). As a means of flood control for the city of Hartford, both North and South branches have channelized sections near their confluence which discharges via a twin-barreled conduit into the Connecticut River. While flood control projects implemented over the last century have protected the City of Hartford from the type of catastrophic floods that occurred in the 1930s and 1950s, channelization and burial of portions of the Park River have dramatically altered the hydrologic and physical characteristics as well as the habitat of the river (Fuss and O'Neill, 2010).

METHODOLOGY

Using %IC as an index of stream health, the effect of watershed-wide reduction in IC on stream hydrology was examined to provide the insight necessary to develop a holistic watershed management strategy (Bellucci et al., 2008). The USEPA Stormwater Management Model (SWMM; version 5.0.022, released in April 2011) was employed using a previously constructed and validated hydrologic model for the Park River watershed (created by CDM Smith, Inc., Cambridge, MA) to assess the effect of reducing IC on stormwater runoff and the hydrology of urban streams. For this assessment, three event-based stream metrics (runoff magnitude, peak flow rate, and time to peak) were evaluated and compared across various urban stream locations within a watershed. Event-based metrics allow for comparison of the impact of storm magnitude and are consistent with the use of specific storm sizes (i.e., return periods) in the design of stormwater controls and management plans (Egderly et al., 2006). Event-based metrics, when compared with the use of historical data, also reduce modeling run time and allow for the comparison of different land cover scenarios across a constant – a specific modeled event –

rather than variable periods of precipitation within the historical record. Five IC reduction scenarios ranging from 0% IC reduction (the base case scenario) to 30% IC reduction were examined to explore the changes to event-based stream hydrology metrics as a result of decreasing IC in an urban watershed. An upper assessment limit of 30% IC reduction was selected based on prior work demonstrating that, in dense urban areas, possible IC reduction is limited (Hazen and Sawyer, 2012).

The Park River Watershed Hydrologic Model

SWMM was chosen due to its ability to model continuous or single-event precipitation simulations and because an existing, verified model of the watershed was available (Heineman, et al., 2010; Huber, 2003). While SWMM is frequently used as a watershed model to represent specific components of an urban stormwater system, very few models have addressed urban collection systems simultaneously with watershed runoff and groundwater contributions to streams (Heineman, et al., 2010). An integrated Park River sewershed model was constructed, calibrated, and validated for the Park River watershed by CDM Smith, Inc. (Cambridge, MA) at the request of The Metropolitan District Commission (The MDC; Hartford, CT). This particular model has 3351 catchments and is rare among urban watershed hydrologic models in its inclusion of the sanitary and storm sewers, watershed runoff, and groundwater contributions to both the stream and the combined piping network. As reducing IC will enhance infiltration, the potential feedback to the engineered system via contributions from a rising groundwater table may be significant (Crites and Tchobanoglous, 1998).

The CDM SWMM model used in this assessment has been calibrated and validated to numerous datasets including flow meters at 27 locations throughout the combined, sanitary and

stormwater systems of Hartford. These data are supplemented by depths measured continuously at 80 CSO regulators, long-term continuous flows at the Water Pollution Control Facility (WPCF), 12 permanent flow meters at Hartford's borders installed in 2008, detailed flow metering in the outlying communities from 2005 and 2009, daily flow records on eight streams collected by USGS between 1936 and 1986, and 60 years of monthly observations by USGS at a water table well in a nearby town (Heineman et al., 2010). For this particular model, the 0%IC reduction scenario uses 2006 land cover conditions as an input file. This land cover data is based on satellite imagery and was obtained from the Center for Land use Education and Research (CLEAR; http://clear.uconn.edu/projects/landscape/project.htm).

Experimental Approach

For this analysis, LID is modeled by reducing total IC in each of the 3351 catchments in SWMM. The initial assessment was conducted without altering watershed %IC with the goal of determining a baseline total volume of runoff created for selected storm sizes. Subsequent input files were created to model a watershed wide reduction in %IC ranging from 5% to 30%. Since watershed IC conditions are typically expressed as a percentage of the total land area with target values given similarly rather than as a fraction of the initial value in watershed planning and management, IC was reduced using a total impervious area (TIA) method of reduction to mimic standard practice (Schueler, 1994). TIA is defined as the fraction of the watershed covered by constructed, non-infiltrating surfaces such as concrete, asphalt and buildings (Booth and Jackson, 1997). The TIA method of IC reduction represents a direct subtraction of %IC from the initial %IC. Previous research has shown that the calculation of IC reduction using the TIA method is more effective at reducing total watershed runoff than the effective impervious area (EIA)

method where runoff is re-routed to pervious cover for storms greater than the 1-yr storm event in this model (Fleischman et al., 2014). Since storm sizes ranging from the 1-yr through the 20-yr event were assessed, the TIA method of IC reduction was utilized for all storm events for consistency in IC reduction method.

Model subcatchment data were modified for each assessment to incorporate a specified reduction in TIA for five scenarios ranging from the baseline case (0% IC reduction) to a 30% IC reduction scenario (0%, 5%, 10%, 20%, and 30%). Initial assessment included 12 locations (Figure 3; Table 1) chosen to correspond to field sample collection and to evaluate potential hydrological changes in the streams along the urban gradient. Following initial assessment, two sub-sets were evaluated in greater detail (1) to highlight changes along the urban gradient of the South Branch of the Park River and (2) to compare a group of small, similarly-sized watersheds with varied initial %IC (Table 1).

For each scenario, the ability of LID to restore the "natural" hydrologic conditions – an objective of LID BMPs – was assessed through comparison of total runoff, peak flow rate, and the time to peak flow rate. For this assessment, we defined the total volume of runoff (Q_{total}) as the total amount of water leaving the watershed above baseflow. Q_{total} is a stream health metric that provides a general measure of habitat availability or suitability (Richter et al., 1996) and reflects conditions of relative hydrologic consistency (Poff and Ward, 1998). Baseflow was determined by projecting the pre-event baseflow under the time of peak (t_p). At t_p, the base-flow separation line rises to a point on the recession limb that is N days after the peak, where N(days) = $A^{0.2}$ with A being the drainage area in square miles (Dingman, 2002; Dunne and Leopold, 1978). Using this method, baseflow was accounted for and removed in the assessment of Q_{total} to obtain only the excess runoff produced and the duration of the runoff event. In addition to Q_{total},

the magnitude of peak flow (Q_p) and changes in the timing of the peak flow (t_p) were assessed to determine the degree to which reducing IC would alter flow conditions relative to baseline conditions. As a result of urbanization, t_p generally occurs earlier in a storm event than in a more rural watershed (Walsh et al., 2005(b), Schueler, 1987). This earlier t_p indicates that water is conveyed through the watershed to the stream more rapidly and is typically related to increases in peak stream flow. An increase in the magnitude of peak flow, Q_p, can cause severe stream channel erosion and flooding downstream (Poff et al., 1997). The most commonly observed effect of an increase in Q_p is the physical degradation of the natural stream channel which likely leads to the destruction of the in-stream aquatic habitat (Roesner et al., 2001; Poff et al., 1997) and reduces hyporheic interactions (e.g., Groffman et al., 2005). For this assessment, both Q_{total} and Q_p were normalized to watershed area as a means of comparing watersheds of different sizes.

Model simulations were performed for each %IC reduction scenario across a range of storm sizes. Using data from Miller et al. (2002), Department of Commerce (1961), Connecticut Stormwater Quality Manual (CT DEEP, 2004), and MDC (2004), the 1-yr, 2-yr, 5-yr, 10-yr and 25-yr, storm events were evaluated using storms simulated according to the Soil Conservation Service (SCS) method (Table 2). All initial runs were modeled using a 24-hr, Type III storm event. Since typical stormwater treatment practices are designed for the 2-yr, 24-hr design storm and green designs are typically designed to retain the volume of runoff generated by 1 inch of effective rainfall, the minimum storm event evaluated for the region was the 1-yr storm (Medina et al., 2011; Garrison and Hobbs, 2011; CT DEEP, 2004; Prince George’s County, 1999). While the 1-yr, 24-hr storm event in this region of Connecticut typically produces 2.7 inches of rainfall, the runoff from this rainfall will vary based on watershed storage and antecedent moisture

conditions. The 1-yr, 24-hr storm was selected as the minimum storm event for analysis despite the fact that it is less than the stormwater treatment design storm because it creates enough precipitation to test the effectiveness of LID implementation in the region. Assessment of the larger, less frequent rain events is also critical in evaluating the potential for LID to protect streams from the associated increased runoff volumes which challenge the ability of LID to reduce runoff quantity (Pitt and Clark, 2008). Additionally, since the chance of an increase in Q_p and a decreased in t_p associated with these larger storms is more certain, an assessment of the ability of LID to reduce the impact of these larger storm events on stream geomorphology is critical when assessing the effect of LID on stream health.

Following the initial assessment of stream health metrics relative to IC reduction for a range of storm sizes, the impact of storm intensity and pre-event watershed wetness condition were examined. Shorter, more intense events may overwhelm BMPs leading to increased runoff. Similarly, wetter pre-event conditions may also increase the runoff generated during storms. The effect of storm intensity was evaluated by comparing results for the 1-hr and 6-hr storm event intensities for the 1-yr event (Miller et al., 2002) for each %IC reduction scenario with those from the 1-yr, 24-hr storm event (Garrison and Hobbs, 2011; CT DEEP, 2004; Prince George's County, 1999). To simulate a typical moisture condition for this watershed, the watershed antecedent precipitation index (*API*), a rough representation of the initial soil moisture condition, was determined from analysis of regional precipitation data from January 1, 2010 to July 1, 2012 (Benkhaled et al., 2004). Using this region's average *API* value, a representative 28-day precipitation pattern necessary to achieve the required *API* value on the day of the created rainfall event was determined. A review of this same period of historical data revealed that, on average in this region, a precipitation event occurred every 5-days. Therefore, when creating a

precipitation file to mimic an average watershed wetness condition, a rain event was inserted every 5-days with the intensity adjusted to achieve the desired *API* on the day of the storm event. To assess a regionally realistic, dry pre-event moisture condition, the smallest storm event recorded during the period of assessment, 3-mm, was entered as the input rainfall event leading up to the created storm event. The watershed was also assessed under an initially wet surface condition. To achieve this wet condition, the baseline rainfall intensity was increased leading up to the simulated rainfall event to increase the *API* on the day of the precipitation event by one standard deviation relative to the average *API* value for the period.

RESULTS

Total Runoff (Q_{total})

Modeling evaluated the impact of %IC reduction for five storm event durations across twelve stream locations (Supplemental Information, Table S1) with Q_{total} decreasing as IC is reduced. Results were evaluated relative to the %IC reduced as well as the %IC remaining to account for differences in the initial watershed IC. The highest reductions in Q_{total} occurred at *wsh1* site in the North Branch and *trt1* in the South Branch (Table 3). For assessment of Q_{total}, each of the twelve sites was normalized by the contributing watershed area to eliminate the influence of area variation when comparing discharge (mm/day).. A 5%IC reduction decreases runoff by up to 16% for the 1-yr event. For a 30 %IC reduction, the runoff decreases by 68 to 88%, with runoff eliminated for *bas1, bas2* and *pip1* (Table 3). For the 1-yr design storm, results demonstrate the runoff can be eliminated with a reduction in %IC. As storm size increases, runoff reduction potential decreases. For example, runoff reductions for the 25-yr event were 11-24% and 71-87% for the 5% and 30% IC reductions, respectively.

Similar responses for runoff relative to the %IC remaining were demonstrated regardless of differences in initial %IC and watershed area. Although watershed %IC influences runoff, connectivity of the impervious areas can lead to variations between watershed responses. An assessment of the three urban gradient sites (*trt4*, *trt1* and *spk1*; Figure 7b) revealed that *trt1* (with average initial %IC and contributing area values between *trt4* and *spk1*) exhibited the highest runoff for each storm and the greatest reduction in Q_{total} as %IC reductions increased. Closer examination of smaller, similarly-sized watersheds focused on the varied initial %IC of 43, 26, 16 and 6% for *mil3, wsh1, wsh2* and *tum2*, respectively (Figure 7a),. Despite the differences in initial %IC, *mil3* and *tum2* experience similar Q_{total} for the 1-yr, 24-hr storm event at each %IC reduction (Figure 7a). The site with the lowest initial average %IC value (*wsh2*) demonstrated low Q_{total} with only a minor reduction. However, the downstream site, *wsh1*, exhibited the highest runoff of any site (Table 3). Despite the fact that average %IC at *mil3* is 17% greater than at *wsh1*, there is almost 39mm/day less runoff.

Peak Runoff (Q_p) and Time-to-Peak (t_p)

Evaluation of the magnitude of peak flow (Q_p) and the timing of peak flow (t_p) across all sites and storm events demonstrated reductions in Q_p as IC is reduced (Table 4). The largest reductions in Q_p for a 30 %IC reduction occurred in the North Branch at *wsh1* where Q_p was reduced by 44-mm/day. For the South Branch, the largest reduction occurred at *trt1* for which Q_p decreased by 25-mm/day. A 5% reduction in IC decreases Q_p by between 0 and 35% for the 1-yr event. With a 30 %IC reduction, a reduction in Q_p of 20 to 98% was realized. For the 1-yr design storm, results demonstrate that peak runoff can be eliminated by reducing %IC (Table 4) at *bas2, bas1*, and *pip1* with a 30% reduction in IC. As storm size increased, less peak flow

reduction was realized. For the 25-yr event, peak runoff reductions ranged from 5-33% and 71-99% for the 5% and 30% IC reductions, respectively.

An assessment of the three urban gradient sites (*trt4, trt1* and *spk1*) revealed similar trends in terms of Q_p reduction for all three sites regardless of differences in the initial %IC and contributing watershed area (Figure 4d). With the highest initial Q_p (30-mm/day), *trt1* exhibited the greatest overall Q_p reduction for the 30%IC reduction for the 1-yr storm event. And although *spk1* has a higher initial %IC relative to *trt4*, the Q_p values were similar across %IC values (Figure 4d).

An assessment of Q_p for the four similarly-sized watersheds with varied initial %IC (*wsh1*, *wsh2*, *tum2* and *mil3*; Figure 4c) demonstrated a variation in the magnitude of reduction Q_p. Although differing in the initial %IC, Q_p values of *tum2* and *mil3* were similar at 18- and 19-mm/day, respectively. Reductions in Q_p for wsh2 were minor; however, the site had the lowest initial %IC and the baseline Q_p value of 0.5-mm/day was the smallest of the assessed sites. The fourth site considered, *wsh1*, has an initial %IC of only 26% yet produces the largest Q_p of all stream sites assessed, 66-mm/day. Consequently, *wsh1* also demonstrated the greatest Q_p reduction (44-mm/day) as %IC was reduced by 30%.

For all sites assessed, t_p occurred slightly earlier as a result of reducing IC (data not shown). This finding is indicative of the urban setting and is a result of the high %IC in the watershed. As IC decreased, the total runoff and Q_p decreased. However, the primary runoff reduction was reflected in a flattening of the hydrograph. The changes in the shape of the hydrograph had very little effect on t_p.

Intensity and Pre-Event Moisture Condition

The storm intensity assessment between the 1-hr, 6-hr, and 24-hr durations of the 1-yr event revealed, as seen with the previous assessment, that runoff volume decreased with %IC reduction regardless of intensity and that the largest amount of runoff is generated for the 24-hr storm duration (Table 5). Runoff decreases as duration decreases. Trends for the reductions in %IC mirror those of the previous analysis. For example, reducing %IC by 30% at *wsh1*eliminates 69, 88, and 72% of the runoff generated during the 24-hr, 6-hr, and 1-hr duration storms, respectively. For Q_p, as storm duration decreased from 24 to 6 hours, peak runoff increased at every site (Table 5). A further decrease in storm duration, to 1-hr decreased Q_p relative to the 24-hr event at every site except for *tum2*. Again, the trends in %IC reduction mirror those previously given. As %IC is reduced, Q_p decreased. No additional benefit was realized by combining %IC reduction and a decrease in storm duration. For example, at *wsh1*, Q_p decreased by 67% for the 24-hr event and 23% for the 1-hr duration for a 30% IC reduction relative to baseline.

The assessment of the three watershed pre-wetness conditions (dry, average and wet) demonstrated no changes in the hydrological conditions of Q_{total}, Q_p and t_p for the 1-yr, 24-hr storm event. Storms with lower return frequencies involve greater total precipitation and may vary depending on watershed wetness. However, for the typical design storm (1-yr, 24-hr) pre-event conditions are not predicted to influence watershed runoff.

DISCUSSION

Runoff results align with prior findings in that as IC increases in this watershed, more discharge is generated (Table 3) and peak flow rates increase (Table 4). Previous research determined that

runoff generation depends on rainfall event (Niehoff et al., 2002) and studies have shown that as IC increases, runoff volumes and peak flow rates increase (Brezonik and Stadelmann, 2002; Finkenbine et al., 2000; Corbett et al., 1997). For a 20% IC reduction, one-third of the assessed stream sites continue to experience runoff values for the 1-yr, 24-hr storm event. Reductions of 30% IC reduced runoff by 69% (*mil3* and *wsh1*) to 100% *(bas1, bas2*, *pip1*; Table 3) and the greatest total reductions occurred for *wsh1* and *trt1* (Table 3). These two sites had the highest baseline runoff. Relative to prior studies, our hydrologic results support the potential use of LID as a component of a stream health improvement plan.

Assessment results demonstrate that while %IC and a large contributing area both play a role in the generation of runoff; they are not solely responsible for urban stormwater runoff. For example, *tum2*, a site with one of the smallest contributing areas and one of the lowest initial average %IC (16%), experienced stormwater runoff for all %IC scenarios in range with the other stream sites with larger initial %IC and larger contributing areas (Table 3). Runoff is generated from watershed locations not included in IC. Additionally, for sites *wsh1* and *trt1*, the only two stream sites examined in this assessment that are at the confluence of two streams, runoff volumes were the highest of the twelve sites assessed. The relatively high runoff with the immediate increase in watershed site suggests that the maximum flow length should be included in the evaluation.

Evaluation of Q_p also suggests that a separate factor other than watershed area or %IC may influence hydrologic response. For the eight stream sites that met the 12% IC recommended value, Q_p was reduced between 44 and 67% with a 20%IC reduction for the 1-yr storm (Table 4). The greatest total reduction in peak flow occurred at *wsh1* where the initial Q_p of 66-mm/d was reduced by 28-mm/d to 38-mm/d with the 20%IC reduction. As with Q_{total}, the watershed sites

with the highest baseline Q_p experienced the greatest Q_p reduction as IC was decreased. Assessment of the two subsets of watersheds demonstrated results for Q_p similar to those for Q_{total} (Figure 4a-d). Among the urban gradient sites, the *trt1* site has a higher baseline Q_p and experiences the greatest reduction despite being the middle site along the urban gradient in terms of location, initial %IC, and contributing area (Figure 4d). Perhaps this is related to *trt1* being located at the confluence of two streams. A similar result occurs within the similarly-sized subset for *wsh1*, the other site located at a stream confluence (Figure 4c). The Q_p at *wsh2* was initially low and therefore reductions are minimal.

The relationship of IC to the hydrologic response suggests that non-hydrologic factors may be the determining factor in stream health. Several sites within the watershed can be reduced to below the recommended value of 12% IC for macroinvertebrate community success (Bellucci, 2007) Channel instability and abrupt declines in indices of aquatic ecosystem integrity have been documented to to occur between 10% to 20% TIA (Brabec et al., 2002; Bledsoe and Watson, 2001; Schueler, 1994; Booth, 1990). With a 20% IC reduction, the average %IC of the stream sites would range from 23% at *mil3* to 0%IC at *wsh2* with four sites (*spk1, bas1, pip1* and *mil3)* greater than the recommended 12%IC (Table 1). Yet, runoff reduction at these three of the sites is >50% relative to baseline conditions, with *mil3* remaining at 56%. Other locations would contain %IC less than the threshold (6-10%) (*wsh1*, *npk2*, *npk1*). Yet, runoff remains >50% of the baseline value with *trt1* and *wsh1* continuing to produce runoff greater than 10-mm for a 1-yr, 24-hr storm event. However, the runoff is generated at four locations (*wsh1* – 17 mm; *tum2* – 8 mm; *trt1* – 3 mm; *trt4* – 2 mm) with 0% IC. Conversely, runoff from the 1-yr event was eliminated at two locations with %IC of 6% (*bas1*) and 9% (*pip1*). The disparity in runoff response demonstrates that natural processes may influence watershed runoff, challenging

restoration efforts based solely on %IC. Additionally, runoff removal with IC present suggests that non-hydrologic factors (e.g., chemical inputs) may be the determining factor in stream health.

Storm event intensity demonstrated an impact on both total runoff and peak flow. Q_{total} increased with storm duration at all twelve sites (Table 5) as the amount of precipitation increased (Table 2). Further analysis showed that as %IC was reduced, the largest percentage of runoff could be eliminated with LID for the 1-yr, 6-hr storm event relative to the other events. For the shorter duration 6-hr event, less rain occurs allowing the installed LID to capture more of the runoff. For the 1-yr, 1-hr event, still less rain falls, but the rate of rainfall is increased relative to the 6-hr event which reduces the pervious surfaces ability to infiltrate the precipitation. The 1-hr storm event is still able to reduce more runoff at the 30%IC reduction than the 24-hr event. An examination of Q_p under baseline conditions illustrates a decrease in Q_p for the 1-hr storm relative to the 6-hr event as the total precipitation decreases. An increase in total precipitation coupled with rapid hydrologic delivery to the stream in the urban watershed results in an increased peak flow rate for the 6-hr event. Increasing the storm duration to 24-hrs, however, lowers the rainfall intensity which allows more time for the water to move toward and enter the stream. This slower delivery accounts for the larger Q_{total} value accompanied with a decrease in $Q_{p.}$ The assessment of intensity variation suggests that changes in the design storm to shorter durations may inhibit the ability of LID measures as part of watershed management plans.

Our results suggest that although limitations to hydrologic performance exist, LID can be a viable component of a stream health management plan. Runoff reductions and Q_p decreases demonstrate that LID will be ineffective for larger storms. As storm size increases, the ability of a practical urban IC reduction (an IC reduction of 30% or less) to reduce runoff and minimize

changes to Q_p diminishes. However, this limitation should not preclude the use of LID as a stream health management technique. Large storm events stress stormwater mitigation measures that aim to control damaging hydrological conditions to streams (habitat destruction, sediment scouring and flushing of aquatic organisms; Pitt and Clark, 2008). Current approaches to LID implementation account for this impact by targeting smaller storm events. The control of smaller events, those that produce less than 38.1 mm of rainfall, is paramount since these more frequent storm events account for the majority (~70%) of annual runoff volume (Pitt and Clark, 2008; Roesner et al., 2001). The elimination of runoff from these smaller storm events will provide longer periods of time between disruptions to the stream channels that will allow for the stream to "recover" (Paul and Meyer, 2001).

CONCLUSION

By modeling event-based stream flow metrics, the potential of a watershed-wide reduction in IC as a component of an urban stream health improvement plan was examined. In the watershed examined, results show that LID, modeled as a reduction in %IC, can greatly reduce stormwater runoff and peak flow in an urban watershed through a reduction of initial %IC by ≥20% for the 1-yr storm event. Reducing baseline IC by 20% decreases the average %IC to a range of 0% to 23%IC with resultant %IC in eight of 12 stream sites below the recommended value or 12% IC for stream health. Stream hydrology responds to the implementation of LID with multiple sites demonstrating the elimination of runoff for 30% IC reduction. However, LID implementation in such a highly-urbanized watershed is complex. Runoff is not reduced or eliminated at many sites even for a 30% IC reduction under a 1-yr storm event. For this watershed, assessment indicates that factors in addition to contributing area and %IC have a

hydrologic impact. The two stream sites located at confluences have the greatest total and peak flow indicating that stream length may factor into runoff reduction assessment. Our assessment suggests that while IC reduction can be an integral component of a stormwater mitigation plan, the application may be limited in an urbanized setting.

ACKNOWLEDGEMENTS

We thank M. Heinemann from Camp, Dresser and McKee, Inc. for guidance and assistance with SWMM, S. King for his extensive assistance with GIS and for performing initial runs in SWMM, and the MDC for approval to use the model.

Evaluating Low Impact Development as a Mitigation Strategy for Alleviating Combined Sewer Overflows within a Connecticut Watershed

Submitted to Water Research Journal

ABSTRACT

Combined sewer systems, designed to collect both stormwater and sewage, are present in 700 United States cities. These systems were designed to overflow during precipitation events, discharging stormwater, toxins, pathogens, and human and industrial waste to nearby surface waters. We investigated the effectiveness of low impact development (LID), a method of preserving natural watershed hydrology, for reducing combined sewer overflow (CSO) at the watershed scale. An EPA Storm Water Management Model (SWMM) of the Park River Watershed in Hartford, Connecticut is used to evaluate the effect of reducing impervious cover (IC) on CSO. To simulate green infrastructure, simulations were performed for IC reductions up to 30% for storm recurrence intervals from three months through 50 years. Hartford's target for CSO control in most areas of the city is the elimination of CSO in a "typical" year. When a 5% reduction in IC is simulated, runoff for a 1-year design storm is reduced 13 million gallons (MG) from a base case of 74 MG, and three of 44 initial overflows are eliminated. A hypothetical 30% IC reduction reduces runoff by 58 MG, eliminating 23 CSO locations. Overflow volume reduction continues to increase for all storm sizes; however, the number of CSO eliminated decreases. In a 25-yr storm, no CSO is eliminated with a 5% IC reduction. Results demonstrate that although LID implementation reduces stormwater volume, LID alone cannot eliminate CSO in Hartford for the storm sizes and IC reductions considered. While cost analysis demonstrates the financial benefit of using grey infrastructure in tandem with green infrastructure for stormwater management, the practicality of LID implementation may not exist. Watershed-level modeling, such as that performed in this investigation, can be useful in identifying target areas for LID implementation, avoiding costly individual hydrologic analysis of LID features during each design.

Keywords: Low impact development, combined sewer overflow, stormwater, urban area

INTRODUCTION

Combined sewer systems (CSSs), which collect both stormwater and sanitary waste, are present in 770 communities throughout the United States and result in approximately 40,000 overflow events each year (Belling et al., 2002). During precipitation events, the single-pipe CSS is overwhelmed by the influx of stormwater and, by design, spills into nearby streams and rivers. Combined sewer overflow (CSO) delivers contaminants associated with stormwater runoff and untreated wastewater to nearby water bodies (USEPA, 2004). The negative effects of CSO have been demonstrated by high levels of pathogens (e.g., States *et al.*, 1997) in streams where combined sewers overflow. Elevated densities of both fecal coliform and streptococci, indicators of human waste, have been measured in riverbeds around CSO outfalls for up to two weeks after an overflow (Irvine and Pettibone, 1993). CSO adversely affects water quality and are considered a water pollution source (USEPA, 2004).

Green stormwater infrastructure, a form of low impact development (LID), is an approach to stormwater control that combines resource conservation, hydrologic site design, and pollution prevention to reduce the impact of the built environment on natural hydrology and minimize negative impacts of urbanization on water quality. LID is considered an alternative stormwater management approach to “grey infrastructure” (Grumbles, 2007). Conventionally, stormwater has been managed using grey infrastructure, which directs stormwater as quickly as possible into a piped network. Grey infrastructure approaches that have been used to reduce CSO have included sewer system separation, underground storage, and/or increasing treatment plant capacity (Hazen and Sawyer, 2012). Conventional implementation of grey infrastructure for CSO mitigation can be expensive due to the costs involved during both construction and repair. Additionally, maintenance to fix aging pipes can be costly (USEPA, 2012(a)). Green infrastructure offers an alternative, possibly cheaper, alternative.

The cost savings from green infrastructure arise from volume reduction and/or peak attenuation and therefore a decrease in the necessary grey infrastructure capacity. Green infrastructure utilizes predominantly natural processes such as infiltration and evapotranspiration, as well as rainwater reuse, to manage storm flows by mimicking pre-development hydrology. Although green infrastructure costs are highly variable, implementation costs have been demonstrated to be lower relative to grey infrastructure approaches (Hazen and Sawyer, 2012). Implementation of LID decreases impervious cover (IC) within each

subcatchment of a watershed, promoting infiltration and decreasing surface runoff (Fuss and O'Neill, 2010). The goal of LID as a management strategy is to decrease peak flow and the volume of stormwater discharged into storm drains and water bodies during precipitation events (Dietz, 2007). LID approaches have been shown to reduce or even eliminate overflows in response to 1 in storms (Hazen and Sawyer, 2012; Garrison and Hobbs, 2011), particularly at a site level. However, as storm length and intensity increases, LID effectiveness decreases. Larger storms produce higher runoff volumes, resulting in significant flooding and CSO volume contributions. Yet, LID approaches may be sufficient to mitigate the smaller, regulated events which vary by location but typically involve 0.3 month to 1-yr return events. Although LID cannot prevent flooding during larger events, runoff reduction results in a decrease in pollutant loading to receiving waters (Garrison and Hobbs, 2011). In addition to hydrologic and pollution control, secondary benefits of LID include additional green space, reduced downstream flooding, erosion prevention, improved quality of life for the surrounding community (USEPA, 2012(b); Garrison and Hobbs, 2011; Roseen et al., 2011; CNT, 2010) and traffic calming (SPU, 2010; Coffman, 2001).

Due to the potential cost savings and the secondary benefits to the community and the environment, the United States Environmental Protection Agency (EPA) has recently promoted use of LID/green infrastructure as part of CSO abatement plans. CSO sites are required to be evaluated for LID approaches as an alternative mitigation approach to grey infrastructure. Many United States cities, including Milwaukee, Philadelphia, Portland, and Seattle, have begun to implement LID throughout the metropolitan area and included LID in their respective CSO abatement plans. EPA CSO policy states that four overflow events are permitted for a CSO outfall in an average year, and that an average of 85% of the volume generated per event should be eliminated or captured (USEPA, 2009). However, these values are targets; mandates for specific cities may be more stringent as each agreement with EPA is negotiated separately. Elimination of CSO through LID alone is challenging as the volume of runoff generated in dense urban areas overwhelms green infrastructure capacity. Implementation plans which include LID typically include a mixture of green and grey infrastructure, but are dominated by grey (Hazen & Sawyer, 2012; USEPA, 2011(a)). Typically, the method of green infrastructure assessment is a bottom-up approach, focusing on implementation of different types of LID based on available locations within a watershed (Philadelphia, 2011; Fresh Coast, 2011). Areas implementing

and/or promoting LID assume a uniformity of performance regardless of watershed location and scale up site-specific performance rather than evaluating system-wide effectiveness of a given LID approach. Few cities have followed watershed-wide, top-down LID implementation. This approach focuses on determining the extent to which LID can be part of a management plan through identification of locations where LID can have the largest CSO reduction benefit.

We propose that the focus of LID implementation should be a top-down approach, not the bottom-up approach that conventional treatment systems use (USEPA, 2012(b)). The top-down approach examines the “big picture” by looking at the needs of the watershed as a whole and then breaks it into components which are further broken down into minute details. EPA is pushing municipalities and companies to use LID in new designs and management plans (USEPA, 2012(b); USEPA, 2011(b); USEPA, 2009). Compared with conventional treatment, LID focuses on restoring and using the natural water cycle. LID treats stormwater close to the source, ideally saving a community’s money as less wastewater is treated. Public health is also protected as less stormwater and wastewater flow into water bodies. As LID techniques become more widespread, the costs associated with LID decrease due to competition among companies (USEPA, 2007). In general, costs vary according to site topography and land availability and usage. One advantage of LID practices, such as rain gardens, is that the technology can be classified as a natural area and left to grow and develop, requiring minimal maintenance (Coffman, 2001).

For this assessment, we utilized a hydrologic model to assess the potential for LID to alleviate CSO. We investigated whether or not LID can be a significant part of a CSO management plan, assessed the impact of storm characteristics on CSO, and examined the potential for targeting specific CSO locations. Utilizing an existing model developed for the Park River Watershed located in Hartford, CT using the U.S. Environmental Protection Agency’s Stormwater Management Model (SWMM), LID was considered by modifying IC in specific subcatchments. Reductions up to 30% of total impervious area were considered for storms ranging from 3-month through 50-year average recurrence intervals. Resultant reductions in estimated discharges can be used to provide direction for managing CSO, particularly in this specific study area. The top-down watershed-level approach will have applicability to similarly affected CSSs.

STUDY AREA

The study area is located within the Central Valley (Figure 5) of Connecticut, specifically the Park River Watershed, encompassing all or parts of the Towns of Avon, Bloomfield, Farmington, Hartford, New Britain, Newington, West Hartford and Wethersfield. The 199 km^2 watershed is characterized by easily erodible sandstone. The western edge consists of steep hills, known as the Metacomet Ridge; however, the terrain flattens eastward toward the Connecticut River (Fuss and O'Neill, 2010). Land use ranges from heavily urbanized in the eastern and southern sections associated with Hartford to undeveloped land in the western portion along the Ridge. Average percent impervious cover (IC) for the watershed is 55%. Generally, impervious area within the watershed consists of transportation infrastructure (parking lots, driveways, roadways) and roofs.

Land development patterns within the watershed and along the river have contributed to the physical and biological degradation of the Park River. The City of Hartford has a combined sewer system built in the late 19^{th} and early 20^{th} centuries that includes 81 CSO outfalls. This CSO delivers raw sewage into the Connecticut River and its tributaries (MDC, 2006) during storms. Many of the CSO outfalls are located in areas with high IC, producing overflow even during minor precipitation events.

METHODS

The magnitude of the reduction of stormwater runoff that occurs when IC is reduced was assessed using EPA SWMM 5. SWMM was selected because a previously verified model of this watershed was available and in use by the Metropolitan District Commission (Hartford, CT; Heineman et al., 2010). While SWMM has the ability to model specific LID features, this investigation focused on watershed-scale assessment to determine the effectiveness of implementing LID as a management strategy and to determine where site-scale implementation would be cost-effective relative to grey infrastructure. Designing from the bottom-up with site-scale determination for each CSO outfall would not be cost effective. A watershed-level top-down model predicts the overall impact at all CSO locations of effectively reducing impervious cover in each of the 3351 modeled subcatchments.

IC reduction scenarios were assessed as the quantity of IC in a watershed has been demonstrated to be a suitable indicator of impacts on the existing stream network (Schueler,

2004; Paul and Meyer, 2001; Arnold and Gibbons, 1996). IC reduction scenarios were evaluated at no reduction (the state of the watershed when the model was created in 2009) and for a 5%, 10%, 15%, 20% and 30% reduction of the IC assigned in the 2009 model. These five reduction values were chosen due to the highly urbanized areas within the watershed where the CSO outfalls are located; some sewersheds contain more than 90% IC. The 30% upper limit was selected as greater reductions in these dense urban areas would be very costly and difficult without major infrastructure modifications, which are generally not plausible (Hazen and Sawyer, 2012; USEPA, 2011(b)). Since watershed impervious coverage conditions are typically expressed as a percentage of the total land area with target values given similarly rather than as a fraction of the initial value, a "hard" reduction was selected to mimic standard practice (Schueler, 1994). A "hard" reduction presents a direct subtraction of the initial IC present in the watershed. If the reduction was greater than the initial value for the subcatchment, IC was set to zero. Allowing the IC for a particular subcatchment to be zero assumes that all impervious cover can either be removed or completely offset by green infrastructure.

Across the range of LID implementation levels, storms with 3-month, 1, 5, 10, 25 and 50-year average recurrence intervals were evaluated. For each storm size, an historical event was selected from 1954 to 2009 data for Bradley International Airport located 10 km north of the study area in Windsor Locks, Connecticut (Table 6). Because actual storms were used for this analysis, average intensity of the storms selected varied. Intensity increased from the 3-month (average intensity 1.5 mm/h) through the 10-yr (11.4) storms before decreasing through the 50-yr storm (7.6). Since storm intensity affects the CSS's ability to contain runoff volume and will therefore limit potential mitigation efforts relative to less intense events, three different 1-yr storm events were evaluated. From historical precipitation records, 7-hr, 15-hr, and 25-hr duration 1-yr events were modeled (Table 7).

Overflow from the CSS was assessed for each storm event and IC reduction level. For each scenario modeled, total watershed overflow volume was determined as follows. The number of "active" CSO outfalls was determined by those generating flow. For each active outfall, total overflow was calculated from the event mean flow for the respective model link multiplied by the overflow duration. To evaluate the effectiveness of the IC reductions on overflows at the watershed scale, individual outfall CSO volumes were summed to give total volume of overflow for each IC reduction for a given storm.

The potential also exists for CSO "hot spots" within the watershed that continue to produce millions of gallons of overflow volume, despite decreased pervious cover within a particular subcatchment (USEPA, 2000). To identify the hot spots and understand which areas should be targeted for stormwater mitigation with LID, each outfall was evaluated to determine the IC reduction necessary to prevent overflows. For each of the 81 outfalls, the breakpoint – the point when the CSS can no longer handle the influx of runoff and begins to overflow – was determined. From a watershed management perspective, efforts to decrease IC should focus on outfalls that can be eliminated by a 30% IC reduction or less. Each outfall was categorized as (1) never overflowing, (2) always overflowing or (3) overflowing up to a specific IC reduction. Outfalls falling into this third category were classified by the IC at which overflow is eliminated.

While IC in the contributing watershed is a widely accepted parameter used to characterize the magnitude of urban development, past efforts to quantify the degree of development have not been consistent (Booth and Jackson, 1997). The most significant issue is the distinction between total impervious area (TIA) and effective impervious area (EIA). TIA is defined as the fraction of watershed covered by constructed, non-infiltrating surfaces such as concrete, asphalt and buildings (Booth and Jackson, 1997). EIA is defined as the impervious surfaces with direct hydraulic connection to the downstream drainage or stream system. Thus, any part of the TIA that drains onto pervious surface is excluded from the measurement of EIA (Booth and Jackson, 1997). We represented IC reductions by direct subtraction from the initial IC rather than as a fraction of initial value (Schueler, 1994). Reducing the TIA using this "hard" reduction approach mimics standard practice.

To assess the impact of the IC reduction method, two EIA scenarios (10% and 30% IC reduction) were selected for comparison with the TIA method results using the 1-yr, 5-yr and 25-yr storm events (Table 6). The 10% and 30% IC reductions were selected to assess a mid-level and the maximum IC reductions. The EIA scenarios differ from the TIA scenarios in that rather than removing IC, an increased amount of impervious surface runoff was routed to pervious cover rather than to the stormwater system. In urban environments with high IC, complete removal of IC may not be practical, but a diversion of runoff to pervious cover may be feasible. Additionally, research has shown that stormwater management techniques that disconnect impervious areas from directly contributing flow to stream channels can improve urban water

quality due not only to hydrologic retention of runoff but also due to removal of contaminants during infiltration (Walsh et al., 2005).

RESULTS AND DISCUSSION

CSO magnitude for each IC and storm combination was calculated using SWMM with overflow volume decreasing as the IC reduction increases (Table 7). Total overflow volumes for the 3-month and 10-yr events asymptotically converged to 5 and 69 MG, respectively, as the IC reduction was increased to 30%. Some outfalls remain active regardless of IC reduction, even for the 3-month event. For the larger storm events (25-yr and 50-yr), although a decrease in the overflow volume occurs, the quantity of runoff overwhelms the CSS regardless IC reduction. For example, for the 30% reduction scenario, the 50-yr storm overflow volume is only reduced to 45% of the baseline scenario overflow (527 MG).

As IC reduction increases, the runoff decreases translate to a decrease in CSO volume. For a 1-yr storm event, the design storm for LID, a 5% IC reduction decreases overflow volume by 18% whereas a 30% IC reduction decreased the CSO volume by 78% (Table 7). While overflow volume reductions increased with storm size, the percentage of reduction relative to the baseline overflow decreased. While over 200 MG in overflow volume is prevented for the 25 and 50-yr storm events with a 30% IC reduction, the percentage of total overflow reduced is ≤66%. Conversely, for the 3-month and 1-yr events, the percentage of total CSO reduced is ≥78%, but with actual overflow reduction limited to 33 and 58 MG, respectively. The reduced effectiveness of IC reduction for the larger storm events demonstrates the difficulty in alleviating the runoff generated during these larger events. However, our results demonstrate the watershed's increasing ability to absorb the majority of runoff with IC reduction for the smaller storms.

In addition to volume reduction, we assessed the ability of LID to alleviate the number of active outfalls for each scenario. The ability of IC reductions to eliminate active outfalls diminished as storm size increased (Table 8) with a limit to the treatable outfalls achieved by the 25-yr storm event. Almost all 81 outfalls became active as storm size increased (Table 8). For the 3-month through 5-yr storms, IC reduction of 30% reduced the number of active outfalls for the 3-month, 1-yr, and 5-yr storms to 16, 21, and 35 from baseline values of 42, 44, and 67 respectively (Table 8). However, even at 30% IC reduction for the 3-month storm, 16 outfalls (20% of the 81 total) remain active. Unlike volume reductions, where the reduction in runoff at

higher events remains large, the reduction in active outfalls diminishes for larger storms. Even for the 3-month storm, the storm size typically regulated, only 62% of active outfalls are eliminated with a 30% IC reduction, demonstrating a likely limitation of using LID for stormwater mitigation in these dense urban areas (Table 8). While LID alone appears unlikely to address EPA mandates regarding CSOs, the elimination of all but 16 outfalls for the 3-month storm demonstrates a potential complementary role for LID in CSO mitigation.

Outfalls that can be prevented through IC reductions for the regulated storm can be identified (Table 8). We identified those CSOs that were treatable using LID for the 3-month storm. Although EPA mandates differ in the permitted allowance of overflows and the regulated storm size, the identification of LID-treatable CSOs is pertinent to other cities. Outfalls that overflow for a given storm regardless of IC, were classified as 'Always Overflow.' Similarly, outfalls that never overflow regardless of IC for a given storm were classified as 'Never Overflow.' For certain outfalls, overflow was eliminated by reducing IC; these outfalls were classified as 'LID treatable.' For the 3-month storm, 16 outfalls 'Always Overflow,' 39 'Never Overflow' and 26 were 'LID treatable' (Table 8). Of the 26 'LID treatable' outfalls, two were eliminated with a 5% IC reduction. Six, five, five and eight additional outfalls were eliminated when IC was reduced by 10%, 15%, 20%, and 30%, respectively. Achieving this reduction in active outfalls would mean that 65 outfalls (39 that never overflow and 26 where overflow can be prevented through LID implementation) or 80% of the CSO outfalls in the watershed would not overflow for the 3-month storm event through only green management (Table 8). Even if a 30% reduction in IC would not be possible due to the existing infrastructure in this urban watershed, a conservative 15% IC reduction would still prevent 52 of the 81 outfalls (64%) from overflowing. For the 1-yr storm event for which the MDC is regulated, the number of outfalls that always overflow increases to 21 with possible overflow prevention of 60 outfalls (37 that never overflow and 23 where overflow can be prevented through LID implementation) at a 30% IC reduction, demonstrating the decreasing effect of LID as storm size increases. The diminished results for the larger regulated storm size demonstrate the increased challenge of including LID in a mitigation plan for cities whose mandates are more stringent.

LID-treatable CSO outfalls provide direction for managers as they weigh options for eliminating specific overflow sites. The list provided via this top-down watershed-level approach supplies managers with a list of sites where more detailed evaluation of green infrastructure is

cost-effective, rather than focusing on where the inclusion of green design would be feasible in this watershed. Data for the Hartford CSS concerning the duration over which each CSO outfall is active during a representative 1-yr event (Heineman et al., 2010) suggest that those identified as “treatable” have shorter durations of overflow. While factors determining overflow duration are complex, physical parameters of the CSS such as overflow weir heights, regulator pipe diameter, pipe size, and network storage may be significant contributors in addition to IC in the watershed. Identifying outfalls that can be eliminated with LID implementation, and the link between reduced stormwater runoff and the physical properties of the CSS, allows a developer to focus on skewing LID within the watershed to maximize CSO elimination. In areas where outfalls rarely overflow, there is no need to implement mitigation. In areas where LID implementation can reduce CSO and space is available, LID implementation is a viable option in place of grey infrastructure.

In addition to storm size, we also assessed the impact of storm intensity for three historical 1-yr storms. A more intense event from August 1962 produced 72-mm of rainfall over the 7-hr period compared with the 63-mm over the 15-hr period used for the baseline evaluation. For a less intense comparison, we selected an event from 12 February 2008 during which 71-mm of rainfall fell over 25 hours (Table 6). Shorter duration, more intense storms increase CSO and decrease the ability of LID to mitigate overflows (Table 9). For the more intense 1-yr storm event, 57 outfalls always overflow as compared with 21 during the baseline event. Additionally, a reduction of only one active outfall occurs for <20% IC reduction for the more intense 1-yr storm event. Should the design storm duration be shortened (intensity increased), CSO-impacted communities will face increased challenges in using LID to prevent overflows.

To realistically assess the feasibility of LID implementation relative to traditional stormwater management, a comparison of the cost of the treatment processes is required. By assessing the annual management costs of runoff and storage associated with the total overflow volume for the 1-yr storm for each IC cover scenario, a cost estimate of the benefit of LID is presented (Table 10). Under baseline conditions, 226 MG of overflow occurs annually in the watershed. Eliminating this overflow using conventional grey infrastructure, at an estimated cost of $0.02 per gal-treated annually (Hazen and Sawyer, 2012), would cost approximately $4.53 M. This value assumes that one 1-yr storm event and four 3-month storm events occurred for this given year. Accounting for the annual cost of stormwater storage associated with grey

infrastructure ($349 M) brings the total watershed annual cost to $354 M for traditional grey infrastructure. Green infrastructure implementation decreases CSO volume and the required grey infrastructure costs (Table 10). LID costs associated with IC reduction have an approximate annual cost of $0.11 per gal-treated (Hazen and Sawyer, 2012). To determine the total cost associated with each IC reduction, the cost of LID implementation was compared with the cost of grey infrastructure and stormwater storage. As the reduction in IC increases from baseline to 30%, the annual cost associated with treating stormwater runoff decreases to $77 M (Table 10) indicating that IC reduction through the implementation of LID in an urban watershed should be considered despite its inability to eliminate all CSO.

Methods for reducing IC in a watershed vary, impacting the watershed hydrologic response. We assessed scenarios representing the two extremes of IC reduction. Complete removal of IC (TIA) represents the maximum benefit of IC reduction while re-routing runoff to pervious cover without making any modifications to the pervious ground cover (EIA) is the least hydrologically beneficial. The difference in hydrologic response between the two methods demonstrates the importance of establishing an IC reduction approach (Figure 2) in mitigation plans. For storms larger than 1-yr, a TIA approach reduced overflow volume more than an EIA approach, regardless of the percent reduction. A 10% TIA reduction outperformed a 30% EIA reduction for the 5-yr and 25-yr events by 16 and 47 MG, respectively. However, for the 1-yr storm event with a 10% IC reduction, the TIA method created 20 MG more runoff relative to the EIA method for the watershed. At 30% IC reduction, minimal runoff was created for either method of IC reduction. These results indicate that for storm events >1-yr a hard reduction in IC (TIA) is more effective than re-routing runoff to a typical urban pervious cover (EIA). However, for design storm events ≤1-yr such as those regulated for CSOs, the runoff volume being re-routed does not overwhelm the pervious area. Therefore, for storm events ≤1-yr, the EIA reduction method is more effective at reducing the stormwater runoff volume exiting the watershed.

CONCLUSIONS

Despite offering significant overflow volume reduction, CSO alleviation is not achieved through implementation of green infrastructure alone. For the Hartford CSS, water quality will continue to be adversely affected as 20% (16 of 81) and 26% (21 of 81) CSO outfalls will

continue to overflow even with a 30% implementation of LID for the 3-month and 1-yr storms, respectively. LID may have greater potential for other CSO-impacted municipalities with less stringent storm mandates. Regardless, the difficulty in addressing the number of permitted active outfalls through reduction in IC alone demonstrates that traditional grey infrastructure techniques should constitute a significant portion of the CSO mitigation plan for the Park River Watershed and similar CSO-impacted areas. Mitigation via LID will become even more challenging as storm size increases as LID works best for low intensity, smaller storm events. For these smaller events, LID is able to perform as designed and retain/treat stormwater close to the source.

While the ability of LID to reduce the number of active outfalls is limited, the volume reduced is significant implying that green infrastructure can be a contributor to a successful mitigation plan. For Hartford, the implementation of a 30% reduction in TIA diminished overflow volume by 33, 58, and 132 MG for the 3-month, 1-yr, and 5-yr storms, respectively. Decreased stormwater runoff volume, as a result of green infrastructure, implies that less grey infrastructure would be necessary which would allow city management to minimize financial resources spent as the stormwater management plan is augmented with LID.

As urban watershed managers look toward the future, projected urban expansion and climate change further challenge the control of CSOs through green infrastructure. Developed areas such as Hartford may not have suitable capacity or willingness for TIA reduction, instead needing to rely on routing stormwater to existing porous areas (EIA). While effective for the current 1-yr event, larger storm results demonstrate the benefit of utilizing TIA as a mitigation metric relative to EIA. Additionally, climate change may increase the intensity of storms, leading to a decrease in the ability of IC reduction to alleviate overflows.

While LID alone cannot completely eliminate CSO, using a hybrid system of green and grey infrastructure would decrease mitigation cost by preventing a significant stormwater volume from requiring treatment. The volume reductions for the 30% IC reduction in TIA are estimated to save $48, $85, and $192 M for the 3-mo, 1-yr and 5-yr storms, respectively. Additionally, the top-down watershed-level approach can predict areas where the implementation of LID will be most effective at eliminating active outfalls, maximizing the use of limited financial resources and potentially decreasing grey infrastructure capacity even further.

Coupling socio-economic considerations with hydrologic evaluation of low impact development implementation in an urban watershed

Submitted to Suburban Sustainability

ABSTRACT

Stormwater runoff, and its associated pollutants, is a major problem in urban watersheds where the runoff is either channeled into surface water bodies or wastewater treatment plants. One emerging Best Management Practice (BMP) to control stormwater runoff is low impact development (LID). The EPA Stormwater Management Model (SWMM) was used to evaluate the hydrologic effectiveness at a watershed scale of five LID technologies (vegetated swales, bioretention cells, porous pavement, rain barrels and tree boxes) in an existing, typical urban watershed. As implementation focused on public transportation areas, hydrologic effectiveness of runoff reduction was assessed as a function of roadway length: and the impacts of LID implementation on traffic flow were modeled using VISSIM and TransCAD. Vegetated swales, the most cost effective option, captured 32% of the runoff with 100% roadway implementation. However, socio-economic factors limit potential mitigation implementation. Transportation modeling demonstrated negative impacts above 4 km of road length (16%), limiting runoff reduction to 2.5%, and non-roadway options such as rain barrels have limited hydrologic effectiveness. While porous pavement can be implemented without impacting transportation, cost is more prohibitive. Combinations of LID features, especially those that do not impact transportation, increase the amount of runoff mitigated. However, socio-economic considerations still limit runoff reduction at the watershed scale to ~15%, less than prior watershed-level evaluations. Our results demonstrate the need to implement LID approaches that account and plan for socio-economic considerations in addition to environmental factors.

INTRODUCTION

Stormwater generation in urban areas represents an environmental challenge and a primary focus of sustainable development (CNT, 2010; USEPA, 2007; USEPA, 2003). Classic stormwater management aimed to rapidly deliver surface runoff from developed lands to streams, lakes and rivers (Seybert, 2006), altering the hydrologic cycle in urban areas by minimizing infiltration to groundwater and enhancing runoff via impervious surfaces (Paul and Meyer, 2001; Arnold and Gibbons, 1996). The resultant hydrologic effect on urban streams has been significant increases in peak discharge, decreases in the time until the peak occurs, and lower levels of base flow in streams (Walsh et al., 2005; Paul and Meyer, 2001). Additionally, runoff from impervious surfaces and roadways delivers contaminants such as heavy metals) to waterways without treatment (Watts et al., 2007). In many older urban areas (e.g., Boston, New York), the combined storm and sanitary sewer system capacity is exceeded during rain events resulting in untreated sewage discharge to nearby waterways (USEPA, 2002). Preventing rapid stormwater delivery to nearby waterways not only decreases water quantity issues but also prevents contaminant loading and is an important mechanism for restoring urban streams.

Since the late 1990’s, the concept of low impact development (LID) has been emerging as a site design strategy replacing conventional methods of stormwater management. The goal of LID is to maintain or replicate the pre-development hydrologic regime by attenuating stormwater locally (Martin et al., 2007). LID aims to mimic natural ecosystem processes and to foster the use of green spaces and plants by encouraging rainfall capture, improving infiltration, and reducing stormwater runoff (USEPA, 2007(b)). Various best management practices (BMPs; e.g., bioswales, bioretention basins, porous pavement, tree boxes, rain barrels) have been used in retrofitting existing development and in planning for new development to achieve improved

landscape hydrologic objectives (Lai et al., 2005; USEPA, 2000). LID site designs, also known as “green” site designs, have demonstrated hydrologic benefits (Hager, 2003; Lehner et al. 1999). Additionally, LID delivers multiple benefits beyond reducing the amount of stormwater; the ecological, economic and social benefits have made green infrastructure an increasingly popular strategy (CNT, 2010). LID can increase green space (USEPA, 2009), enhance property values (CWP, 2010) calm traffic (Matel, 2010; Li and Liu, 2009), increase community walkability, and reduce fatigue, anger, aggression and stress of automobile drivers (Barton and Pineo, 2009). Often, many of these additional objectives are addressed simultaneously with the overall goal of improving community livability (Garrison and Hobbs, 2011; Roseen et al., 2011) and add value to urban communities.

As we explain in more detail in our literature review, several gaps exist regarding LID performance evaluation. In this paper, we seek to address the limited evaluation of hydrologic performance at a watershed level and the lack of an evaluation of watershed-level transportation impacts. Although a need for watershed-level hydrologic assessment has been identified (Lai et al., 2005), few evaluations have been performed. And no prior watershed-level studies account for potential limitations on implementation due to negative transportation impacts. Documentation regarding transportation impacts have been limited to the benefits of traffic calming at the site-scale (Matel, 2010).

To address the gap between LID design and stormwater management decisions with respect to LID watershed scale and socio-economic consideration, we assessed the potential benefits of LID implementation in terms of (1) stormwater runoff reduction at a neighborhood scale and (2) the influence of socio-economic considerations on the decision-making process. We evaluated the ability of various types and coverages of LID features on runoff reduction in a

dense, urban residential neighborhood, located in Hartford, CT. Five different common LID technologies were modeled for runoff using the EPA Storm Water Management Model (SWMM), each implemented in accordance with design guidelines and accounting for the existing transportation infrastructure. We subsequently evaluated the influence of two socio-economic considerations, cost and transportation, to evaluate the impact that non-hydrologic considerations have on LID potential implementation. Traffic impacts were modeled via TransCAD and VISSIM. Our review provides an assessment of the potential for LID features to alleviate stormwater runoff at neighborhood scales under the constraints of space, cost, and traffic flow in an existing urban neighborhood.

A detailed literature review of relevant watershed-level evaluation is summarized. Following the review, we present an empirical watershed-level hydrologic evaluation. We subsequently detail an empirical cost and transportation analysis for the same watershed. Results from these socio-economic factors are then integrated into a decision-making process for LID potential, both within the urban neighborhood studied and similar higher density retrofits.

LITERATURE REVIEW

With initial hydrologic success documented, particularly at the site-level, implementation of LID has transitioned from the pioneering phase to a phase of rapid growth. The application of specific LID designs have been optimized at the site level relative to BMP type, area, depth, and plants as well as site weather, the design precipitation amount, soil type, and percent imperviousness of the contributing area (Montalto et al. 2007; CICEET, 2007; Dreelin et al., 2006). Research efforts regarding LID optimization and implementation at the site level are abundant (e.g., Xiao, 2007; Schneider and McCuen, 2006). However, the implementation of LID

and other stormwater management strategies occurs over multiple spatial scales, from site to neighborhood to watershed levels (Damodaram et al., 2010; Williams and Wise, 2006). Design factors and challenges differ for watershed-level LID implementation relative to concerns at the site level. The distribution of LID within the implementable area, local hydrology, watershed topography, and the layout and type of existing impervious area are key factors that must be considered. Additionally, factors that may be beneficial at the site scale such as traffic calming (Matel, 2010) may inhibit implementation at the neighborhood or watershed level. Neighborhood-wide traffic calming may impede emergency vehicles, commuters, and public transport, the evaluation of which has not been performed. The evaluation and decision for implementation of LID at scales beyond the site level is critical as land use management decisions are typically performed at the neighborhood or watershed scale (Arnold and Gibbons, 1996). The connection between small-scale individual LID performance and watershed-level LID implementation effectiveness is necessary to assess the potential for reduction in stormwater runoff, particularly given the inclusion of LID into recent U.S. Environmental Protection Agency (EPA) directives for stormwater and combined sewer overflow (CSO) management approaches (USEPA, 2007).

In response to the growing use of LID, the EPA has recognized the need for watershed-level assessments of LID benefits and the identification of strategic locations for BMP implementation in urban watersheds (Lai et al., 2005). However, realistic estimates of the ability of LID to reduce stormwater in urban retrofits at the neighborhood scale are limited (Petrucci et al., 2012; Meierdiercks et al., 2010; Bedan and Clausen, 2009). Many planning evaluations at larger scales utilize site-specific information scaled up to the size of interest. Field measurements from a paired watershed study show that post construction storm flow in the LID watershed was

reduced by 42% when compared to a traditional neighborhood built using typical subdivision standards (Bedan and Clausen, 2009). However, the potential reduction likely is more limited in dense, urban watersheds with increased space constraints. While Meierdiercks et al. (2010) demonstrated runoff reductions for a watershed with BMPs implemented, the runoff response was closer to the paired watershed without BMPs than to tthat of the undeveloped control. Modeling investigations predicted that 100% implementation of a mixture of BMPs would significantly reduce the runoff in Paris, France (Petrucci et al., 2012) and Kitchener, Ontario (Zimmer et al., 2007). However, neither study addressed the feasibility of implementing 100% of such a densely developed urban watershed, the costs associated with implementation, the incremental performance, nor social constrains such as transportation. More than 30% reduction in IC has been cited as an upper limit for implementation in dense, urban watersheds based on cost and space considerations (Hazen and Sawyer, 2012). And none of these prior investigations accounted for limitations on implementation due to the need to maintain traffic flow.

STUDY AREA

A small urban watershed located in the northwest section of the City of Hartford, CT, was selected for analysis (Figure 6). The Granby watershed is a sub-section of the North Branch Park River watershed and is characterized as an urban high-density residential neighborhood composed predominantly of privately-owned properties. The 167 ha study neighborhood is contained approximately by Granby Street to the west, Blue Hills Avenue to the east, Burnham Street to the north and Westbourne Parkway to the south. Given the objective of evaluating the potential hydrologic improvement for green BMP implementation along public roadway corridors, roadway characteristics in the neighborhood will influence BMP options and

performance. Total roadway distance in this area is just over 24 km with an average roadway width of 8.55 m (Supplemental Information, Table S1). The widest road, Canaan, is 11.8 m and the narrowest road, Holcomb, is 5.82 m. The highest elevation is in the NE corner of the watershed and the area of study slopes gently southwest with an average slope of just over 2%. The design of this neighborhood typifies an urban residential design layout: the transportation infrastructure is a gridded pattern with wide, curbed streets flanked by pedestrian walkways. Little commercial development exists in the community; less than 7% by area of the watershed is town owned/commercial properties. The street pattern was designed to facilitate travel via vehicle to shopping districts located at the north and south ends of the neighborhood with the majority of residents also commuting to work outside of the neighborhood (L. Hunt, Blue Hills Civic Association, *personal communication*).

The average percent impervious cover (%IC) for the 119 subcatchments in the Granby watershed is 45% but varies significantly by subcatchment from 0.5% to 85.6%. Impervious cover is higher in the lower portion of the watershed relative to the northern part of the study area. Generally, impervious area within the watershed consists of transportation infrastructure (parking lots, driveways, roadways) and roof tops. Roof tops comprise the greatest percentage of the impervious cover within the watershed at 19% of the total land area followed by roads, driveways and parking lots with 14%, 10.6%, and 1.4%, respectively. Soils throughout all 119 catchments have been classified as moderately well-drained sandy and silty loam soils (USDA, 1986). While the base soil is suitable for infiltration and the installation of LID measures, surface soils have been heavily modified, representative of an urban environment, and may differ from the base soil regarding infiltration rate.

METHODS

We evaluated the effectiveness of LID features for minimizing watershed runoff using SWMM Version 5.0.022, a hydrologic model developed and updated by the USEPA (USEPA, 2011(b)). SWMM was selected as: (1) an existing, SWMM model of the area of interest was available (M. Heineman, CDM Smith, *personal communication*) and (2) Version 5.0.022 has the ability to model various LID features including bioretention basins, porous pavement, vegetative swales and rain barrels. SWMM is a dynamic rainfall-runoff watershed simulation model designed for modeling urban areas to predict the resultant runoff from each subcatchment in response to precipitation. Each subcatchment is parameterized by percent pervious/impervious, average slope, storage and infiltration. From these parameters, the model calculates a quantity of runoff relative to infiltration in response to a rain event based on the Green-Ampt Method (USEPA, 2011(b)). In addition to watershed runoff/infiltration, SWMM can incorporate engineered stormwater infrastructure (e.g., stormwater pipes, catch basins) to obtain a realistic understanding of the quantity and fate of urban stormwater. Petricci et al. (2012) provide a more detailed justification for the use of SWMM for evaluating LID at the catchment scale. The Park River sewershed SWMM model obtained from CDM also includes groundwater contributions to streams and the piping network. As LID improvements aim to enhance infiltration, the potential feedback to the engineered system via contributions from a rising groundwater table needs to be considered. Feedback from a rising groundwater due to infiltration in one subcatchment hampering infiltration in a neighboring subcatchment is an aspect unaccounted for in traditional scale-up methodology. The CDM Park River sewershed model was calibrated and verified for the Park River watershed, of which the Granby neighborhood is a subcatchment (Heineman et al., 2010).

To simulate LID implementation, the model subcatchment data was updated to include specific LID designs within the SWMM configuration and used to calculate resultant runoff reduction relative to the base case (no LID) for various types and coverage of LID in the watershed. With the exception of rain barrels, we focused on publicly-owned roadway right-of-ways for our assessment as alterations involving private land require owner buy-in along with an assumed increase in cost and maintenance requirements for the homeowner. Rain barrels were a specific non-roadway option included due to ease of implementation, the benefits to public awareness of stormwater concerns, and the existence of programs to promote distribution. Because most publically-owned land in this dense urban neighborhood is roadway, the potential impact of implementation and design on traffic also was considered when locating and sizing the LID features in the watershed. The impacts of LID features on the transportation network were modeled in transportation simulation models, TransCAD and VISSIM.. We maintained at least one travel lane and one parking lane following LID implementation. Initial traffic pattern modeling indicated that completely closing a street would cause unnecessary congestion on alternate roadways and on-street parking in the neighborhood was maintained to satisfy residents' needs based on surveys and community meetings (data not shown). Our approach highlights a top-down watershed-level implementation evaluation. As such, we did not evaluate specific individual site feasibility, instead focusing on the overall potential for consideration of LID implementation in watershed management decisions. Regardless, regulatory requirements and sizing guidelines set forth by the Connecticut Stormwater Quality Manual (CT DEEP, 2004) for sufficient runoff removal were considered in selecting basic LID model parameters.

Hydrologic Performance

We compared the benefit of each LID feature over a range of percent coverage to assess the potential for each technology to alleviate watershed runoff. We were focused on implementation in the roadway right-of-way, ignoring potential applications on private land. Therefore, the coverage was implemented based on the length of roadway in the watershed retrofitted with LID features. Roadway LID options were implemented from baseline conditions (0 km) in 2 km intervals through 12 km with additional model runs evaluated for 75% (19.3 km) and 100% (24.4 km) of the total roadway length transformed to LID to determine the maximum potential hydrological benefit of LID implementation. The streets selected for implementation were evenly distributed throughout the watershed while accounting for transportation needs and street width LID implementation limitations. Due to public transportation corridors, and the primarily north-south traffic flow, street selection focused on east-west secondary roadways (Table 13). As implementation coverage increased, secondary east-west streets were selected followed by secondary north-south streets. The two primary transportation corridors on either side of the neighborhood (Granby Street and Blue Hills Avenue) were not selected until the 100% implementation scenario as transportation analysis indicated that doing so would adversely affect traffic flow and negatively impact public transportation. Once specific streets were determined for implementation, the roadway length was converted to a total implementable distance in each of the 119 subcatchments for entry into SWMM by assigning the selected streets to their respective subcatchments.

LID Type

The LID features considered for analysis were divided into two categories: (1) roadway – those LID options that would be implemented in the roadway and could potentially alter traffic patterns, and (2) non-roadway – LID technologies that would not interfere with traffic. For roadway options we evaluated vegetated swales, bioretention basins and porous pavement while for non-roadway options we evaluated tree boxes and rain barrels. Given the focus on roadway LID features, implantation within the watershed was expressed as the length of roadway along which LID features were added. The length of roadway correlates to a level of IC mitigated through the design criteria outlined below for the specific LID types. Increased vegetative coverage, a comparatively easy watershed improvement, was not considered as tree coverage is already relatively dense in the current green spaces. Through analysis of aerial photographs obtained from The Metropolitan District Commission (Hartford, CT) of the watershed, approximately 75% of the available green space currently is planted with trees.

LID features were designed as stipulated in Connecticut state stormwater regulations (CT DEEP, 2004). If not specified by Connecticut, design parameters for other states were followed. All LID technologies implemented were designed in accordance with published guidelines: vegetated swales (CT DEEP, 2004), bioretention (Prince George's County, 2007) and porous pavement (ISUIT, 2009). All three LID technologies were designed to accommodate the rainfall volume of a 10-yr, 24-hr storm and the high intensity rainfall created by a 1-yr, 30-min storm as per state guidelines (CT DEEP, 2004).

For bioretention and vegetated swales, the implementable widths of the LID features were determined based on the width of the narrowest roadway considered (7.16 m). Two roads within the watershed are narrower, but were not used for LID implementation except in the

100% implementation analysis. With 6.1 m of paved roadway required for one traffic lane and one parking lane (AASHTO, 2004), the available width of roadway for LID implementation was 1.07 m. Since this distance is insufficient, it was assumed that the grass buffer between the edge of the road and the sidewalk could be included when necessary affording an additional width of 1.67 m for a total width of 2.74 m. The length available for implementation of roadway LID features was restricted by existing driveways. Using aerial photographs, an average distance between driveways was estimated to be 15 m, which was used as the maximum length available for swales and bioretention cell features. The dimensions of each LID technology implemented were adjusted based on design standards (Table 11). For all roadway LID features, the remaining area of the roadway width (6.1 m) was assumed to be captured and treated by the LID feature.

The implementation of the two non-roadway LID technologies was designed to correspond to the implementation distances used for the roadway LID technology. Tree box implementation for each subcatchment was determined using the specific street lengths used for roadway LID and the criterion identified (Table 11). For rain barrels, a ratio of rooftops per roadway length was applied to the street length per catchment to determine the total number of rain barrels to implement within each of the 119 catchments. The ratio of rooftops per distance was determined using an average value estimated visually for the number of rooftops per street for five of the streets within the watershed and applied to the remainder of the watershed. In this watershed, the average roof area per house was 158 m^2 which resulted in approximately 6.1 m^2 of roof area per meter of roadway. We assumed one rain barrel per house with that rain barrel draining half of the roof. This method of calculating rain barrel coverage allowed for an estimated value of the amount of impervious surface that each 590-L rain barrel was able to treat.

The number of houses with a rain barrel increased with each successive model run matching the increase in distance of implementable roadway.

The calculated design area for each LID feature was entered into the appropriate subcatchment in SWMM and evaluated for each runoff reduction scenario. The total runoff for the watershed was computed by summing the runoff from each model subcatchment. Results of each run subsequently were compared to the base conditions for the watershed (i.e. no LID implementation or 0 km of roadway length) to determine a percent runoff reduction. Only the runoff from the appropriate impervious surface (roadway, roof) was assumed to be treated by the LID options that were implemented, ignoring potential runoff contributions to the LID feature from nearby grass areas. While subjected to increased runoff in urban areas due to compaction, grass area is likely to still have higher infiltration rates relative to roof and pavement areas. Simulations were performed using a 1-yr storm event, the minimum design storm for most LID technologies (ISUIT, 2009). Precipitation data collected at Bradley International Airport in Windsor Locks, CT from 1954 to 2009 were used to select a historical 1-yr storm for this assessment. The airport is located approximately 13.7 km north of the study area. We selected a historical 1-yr storm event (April 10, 1983) that produced 6.3 cm of rainfall over a 15-hr period resulting in an intensity of 0.419 cm/hr and was verified to be a 1-yr event using local IDF curves (Miller et al., 2002).

Modeling LID in SWMM

In SWMM, five modeling process layers are available to model LID controls: the surface layer, the pavement layer, the soil layer, the storage layer and the underdrain layer. The surface layer corresponds to the ground surface that receives direct rainfall and run-on from up-gradient

land areas, stores excess inflow in depression storage and generates surface outflow that, in this case, flows onto down-gradient land areas. The pavement layer provides specifics about the characteristics of the particular pavement mix and is used solely when modeling porous pavement. The soil layer is the engineered soil mixture used in bioretention cells to support vegetative growth. The storage layer is a bed of crushed rock or gravel that provides hydrologic storage in the LID feature. The underdrain system conveys water out of the storage layer into a common outlet pipe or chamber. All of the LID controls modeled in SWMM provide some amount of rainfall/runoff storage and evaporation of stored water with the exception of rain barrels (USEPA, 2011(b)).

The variables and criteria for each layer of each LID technology were selected based on recommendations from the literature or the CT Stormwater Manual (CT DEEP, 2004; Table 12). For uniformity among the LID technologies, no underdrain was assumed for tree boxes. The goal of this study was to determine the surface runoff reduction in the watershed. We did not include an underdrain, a common element of tree box design, because we wanted to ensure any excess water would exit the tree box design as runoff rather than directly entering the storm sewer system via the tree box underdrain.

Socio-economic Considerations

Cost

From a practical management standpoint, the implementation cost also affects the selection of a suitable BMP. Costs per unit area of construction were estimated from published values (Table 14) and applied to each LID feature and coverage. Generalized implementation costs were used for the cost estimates selected from within the range of published estimates for the roadway

LID options (Table 14). Costs will vary with site conditions, being highly dependent on location and availability of materials (USEPA, 2011(a)), specific design, local labor and material rates, real estate values, and contingencies (Dreyer, 2012; USEPA, 2011; CICEET, 2007; LIDC, 2005; RRDP, 2001; USEPA, 2000). Values were selected from the upper end of the cost range for the current study due to the high degree of urbanization in the watershed which would require the disruption of the existing impervious cover.

For the two non-roadway options considered, regional cost estimates were utilized. Tree boxes were assumed to cost $2,500 per unit, the actual implementation cost of tree boxes at the UNH Stormwater Center ($US 2007; CICEET, 2007). For rain barrels, 156 gal barrels were chosen for this assessment due to their commercial availability. The assumed cost of installation for each rain barrel is $195 per barrel based on reported average cost of $1.25 per gallon published by the USEPA (USEPA, 2011(a)).

Cost is a key aspect in assessing the practicality of LID implementation. A more thorough examination of the factors affecting the variability of costs and the potential impact that those costs have on influencing LID selection would be beneficial and are detailed elsewhere. Given the focus on a top-down watershed approach, specifically hydrology, a more detailed cost evaluation was beyond the current scope. Regarding our analyses, we present a simplified cost estimate to place the hydrologic benefits in context. A more detailed investigation of the variability in costs requires additional knowledge about the cost distribution functions, without which a uniform distribution would be assumed presenting a trivial assessment. Therefore, while interesting, a more thorough evaluation of the cost uncertainty is beyond the scope of this study.

Transportation Impact

The traditional four-step planning model (Trip Generation, Trip Distribution, Mode choice and Assignment) was used to simulate traffic on the network in TransCAD and VISSIM. Census tract data were used to estimate the number of trips generated from and attracted to each zone within the network producing an origin-destination (O-D) matrix. This matrix was assumed to be static and not impacted by LID improvements. Also for simplicity, the mode choice was assumed to be negligible and not impacted by LID improvements. The resulting O-D Matrix was then assigned to routes throughout the network to get travelers from their origin to their destination. These assignments were made based on the current characteristic of each link of the network. As the proposed LID improvements were applied stepwise to the network, the assigned O-D matrix was updated to reflect the new characteristics of each link. For example, if the 2.4 km of roadway were to be converted to a one-way street with a grassy swale, the links would be changed to one way travel links, thus restricting simulated traffic to use this link only for one way traffic. The resulting change in traffic flow and patterns were noted for proposed LID scenario and level of implementation. Overall changes in vehicle miles traveled (VMT), vehicle hours traveled (VHT) and number of vehicles traveling on each link (flow) were summarized to characterize the watershed-wide traffic impact of the specified LID implementation.

RESULTS

Hydrologic Performance

A comparison of percent runoff reduction to implementation distance along the roadway right-of-way was conducted using SWMM for each LID technology (Figure 7a). Porous pavement, bioretention and vegetated swales were comparable in terms of runoff reduction per

implementable distance. All of the roadway LID technologies assessed ranged from 1.6% percent reduction at the 2 km implementation distance through 33% reduction for full implementation (100% or 24.4 km of roadway implementation; Figure 7a). The trends were approximately linear with variation in hydrologic response with of increased coverage due to street-specific differences (Table 13). Certain streets, and therefore catchments, have a greater potential to reduce runoff with the implementation of a BMP due to their existing %IC and width. Rain barrels and tree box filters were less effective methods, with maximum runoff reduction potential with 100% implementation of 4% and 6%, respectively (Figure 7a). Rain barrels account for a very small decrease in percent reduction due to the relatively small amount of runoff treated. Tree box filters were not as effective in capturing runoff due to their small size (3.34 m^2) and the large amount of space suggested between the boxes (30.5 m) in order to maximize performance (Virginia Department of Conservation, 1999). Decreasing the space between the boxes would increase tree box effectiveness proportionally. Based on the comparison of percent runoff reduction with implementable distance, porous pavement, vegetated swales and bioretention cells would be appropriate options for maximizing runoff reduction in this type of urban watershed.

Socio-economic Considerations

<u>Cost</u>

We then evaluated runoff reduction potential against implementation cost to assess the cost-effectiveness of each LID technology for a given implementation distance along the roadways (Figure 7b). LID options differ in the cost per implementation length (i.e., area; Table 14). Adjusting the runoff reduction performance to account for implementation cost demonstrated

that swales were the most cost effective BMP for the study area. Vegetated swales yielded the highest percent of runoff reduction for the lowest cost for the implementation size, largely due to the lower construction costs ($82.45/m^2$). Construction costs for PP and bioretention cells render these technologies more expensive options. While non-transportation options afforded minimal runoff reduction, the lower costs, particularly for rain barrels, may increase the feasibility of implementation on a larger scale.

Transportation

Transportation impacts increased with 5.7 km of LID implementation (Figure 8). VMT, VHT and Flow increased between 3.8 and 5.7 km of implementation, indicating that vehicles traveling through the neighborhood will have to travel further to complete the same trip (VMT) and require additional time to travel a similar distance (VHT). Flow, a measure of the number of vehicles that travel along a road, summed over all links, indicates that vehicles are now required to take less direct route to get from their origin to their destination. With LID implementation, the number of turns vehicles perform, the roads vehicles travel, and time required to travel from origin to destination increase. These metrics are relatively constant through 3.8 km of implementation before increasing significantly by approximately 4% between 3.8 and 5.7 km of implementation. Above 5.7 km of implementation, the metrics again remain relatively constant through 12 km (50%) of implementation.

DISCUSSION

Full implementation of a single LID stormwater BMP resulted in a maximum stormwater runoff reduction of 32%. In the dense, urban setting evaluated here, the %IC was high which

resulted in a significant amount of stormwater runoff (15.8cm) generated by a 1-yr storm event. Our predictions of LID performance are lower relative to prior studies of complete LID implementation, which cite up to 97% capture (Petrucci et al., 2012; Zimmer et al. (2007). The higher runoff reductions in prior studies for complete coverage result from implementation of a combination of LID types in all available spaces in the watershed. Our results reflect single LID features implemented only in the transportation right-of-way (TROW). Combinations of porous pavement and either swales or bioretention may be possible in the TROW representing a potential capture of nearly 41%, still lower than prior studies. Additional minor runoff reductions of 9.6% could be achieved through simultaneous implementation of the two non-TROW options, tree boxes and rain barrels along with those in the TROW. In all, the total runoff reduction achieved (51%) would still be lower relative to prior studies as we limited the consideration of implementation on private land. Although the complete coverage investigated in prior studies is technically feasible, actual implementation would likely be limited by space, cost, and social preference (e.g., non-willingness to forego parking). Implementation in a dense urban setting has been suggested to be limited to 30% (Hazen and Sawyer, 2012).

Our results demonstrate that transportation requirements may limit the ability to implement LID features on roadways, even secondary arterials. While hydrologic benefits continue to increase with implementation, so do negative transportation impacts. Given the significant increase in transportation metrics above 3.8 km of implementation (Figure 8), stormwater mitigation using roadway LID features is limited in such developed watersheds. Runoff reduction from such implementation would be capped at 2%, significantly less than that with full coverage. The increases in transportation metrics could result from the additional total LID coverage or the selection of specific streets. The low traffic volumes and lack of proximity

for the incremental roadways selected for the 6 km implementation suggest that roadway selection would not have an impact. However, specific street selection was not explicitly investigated. Regardless, local watershed managers need to consider transportation constraints when developing stormwater management plans involving LID.

In the Granby watershed, transportation considerations limit potential implementation of the cost-optimal LID approach to approximately 16% of the road length, a significant reduction from the 24.4 km representing complete implementation. The runoff reduction resulting from the realistic implementation of just one LID technology along 4 km of TROW is minimal. To improve performance, watershed managers could consider implementing a mix of options. In addition to 4-km of vegetated swales (5.0% runoff reduction) PP can be utilized PP for in a different 4-km section of the watershed. With a possible combined runoff reduction of 8% (Figure 7a), swales and PP in concert could provide runoff reduction not possible with the implementation of a single LID technology. Including rain barrels in a combined 4-km scenario at half of the homes in the watershed in addition to the swales and the PP, increases the potential runoff reduction to 11% (Figure 7a). Implementing multiple types of BMPs to achieve watershed goals is encouraged (USEPA, 2004; USEPA, 2001) and could come closer to achieving pre-development hydrologic conditions (Damodaran et al., 2010; Petrucci et al., 2012; Zimmer et al., 2007).

Cost of implementation could inhibit the use of specific BMPs (e.g., PP) and multiple BMPs. Augmenting the watershed implementation plan to incorporate multiple LID technologies (e.g., swales, PP, and rain barrels) would increase the reduction in IC and decrease the runoff; however, the increase in the cost of implementation may be a challenge. Similarly, PP implementation at levels > 4 km may be possible, either for parking or travel lanes. PP would not

alter traffic flow nor reduce parking, but and represents a more expensive option (Table 13). Additionally, PP lacks the short duration storage capacity that swales provide (USEPA, 1999).

Our runoff results demonstrate the incremental hydrologic benefit of LID implementation at a watershed scale and the importance of socio-economic considerations (Figure 7). Many social factors can influence the decision-making process. We have chosen to examine transportation as a representative example to demonstrate the need to include such non-hydrologic considerations in decision-making. Given the limited benefit per LID feature and the cost of implementation, many management plans are implemented based on opportunities as options become available given space and cost constraints (USEPA, 2010). While each LID option is evaluated prior to implementation, an evaluation of the overall hydrologic benefit and potential transportation impacts at the watershed level are lacking. The benefits of large-scale implementation across watersheds has been documented via hydrologic models (Petrucci et al., 2012; Zimmer et al., 2007). As noted by Petrucci et al. (2012), watershed level assessments are a necessity for evaluating policy and planning prior to implementation; yet, many such plans lack the necessary hydrologic evaluation at the catchment level to support decisions on placement. Our study builds on prior watershed-level evaluations (Petrucci et al., 2012; Zimmer et al., 2007) by demonstrating the incremental hydrologic benefits achievable per LID implementation (Figure 7). Additionally, watershed managers need to consider the total amount of implementation allowable given the constraints (including cost and transportation) of the existing built environment during the decision-making process to best assess the optimal location and type of BMP to employ. Our results suggest that transportation will be a limitation on implementation along TROWs and that managers target wider streets for implementation where larger swale size could be implemented without negatively impacting transportation (Figure S1).

While the two non-roadway options do not offer the runoff reduction potential that the roadway options offer, they are worth considering for other reasons. Tree boxes provide the benefit of greenery on an urban sidewalk and could be maintained by the municipality rather than relying on a homeowner for maintenance and up keep. Tree boxes have similar runoff reduction to rain barrels, but may be limited by the higher cost. While offering the smallest runoff reduction, rains barrels represent a very affordable option (Figure 7b). Rain barrels also provide the visual reminder of efforts toward sustainability and stormwater reduction that have proven positive in changing the mindset of a community; individual community members can get involved with minimal financial investment which contributes to generating public support for further LID improvements (USEPA, 2010). Since neither of the non-roadway options impacts transportation, each can be implemented without impacting transportation to increase runoff reduction. However, these features present the challenge of involving private owners in implementation and maintenance.

CONCLUSIONS

Model results indicated that the most cost effective LID technology in such a developed watershed was swales . Relative to prior investigations, the percentage of stormwater reduction using LID was limited in this dense urban settings due to the constraints of predevelopment, with a maximum decrease of 32% for 100% implementation of a single LID technology in the TROW. However, transportation requirements and the limitations of implementing pervious solutions on private land limited the amount of potential mitigation from a single LID technology to 16% of the roadway length in the watershed. Utilizing multiple technologies that are outside of the TROW such as rain barrels and tree boxes, provides a mechanism to maximize runoff

mitigation within the constraint of maintaining traffic flow. PP may also be able to be implemented along the area not treated by swales without negatively impacting traffic metrics, albeit at a higher cost.

When evaluating management decisions, an LID implementation strategy should be employed from a watershed-level perspective for the prediction of stormwater runoff reduction. Additionally, non-hydrologic factors including cost, transportation requirements, and resident preferences will affect LID selection and likely will limit full watershed implementation. While further site-specific assessment would be necessary should LID be deemed a stormwater runoff reduction strategy, an overall evaluation of the potential reduction that includes socio-economic considerations is necessary to determine the role for LID in the overall watershed plan. Assessing the incremental hydrologic benefit of LID features simultaneously with cost and non-hydrologic requirements provides a measure of the implementability of LID in a catchment.

ACKNOWLEDGMENTS

We thank M. Heinemann from Camp, Dresser and McKee, Inc. for guidance and assistance with SWMM, the MDC for approval to use the model, and the Connecticut Center for Transportation and Livable Systems for financial support. We also acknowledge assistance with initial model simulations from University of Connecticut undergraduate students B. Soloway and M. Welch and United States Coast Guard Academy undergraduate students A. Murray, E. Maher, L. Delgado, K. Coleman, J. Bobo, and D. Shockey.

SUMMARY

Looking specifically at the Park River Watershed in Hartford, CT, LID implementation, with a proven success at the site-specific level, was assessed at the watershed level where urban stormwater management decisions are necessarily conducted. The Park River Watershed faces many of the challenges typical of an urban watershed: biologically degraded stream health due to alterations in the natural stream channels, detrimental changes due to the symptoms of the urban stream syndrome, and CSO events that allow raw sewage to directly enter the stream channels during periods of high flow in the CSS. Additionally, due to the constraints of the existing built environment, location and type of possible LID is limited. Through a modeling assessment, the effectiveness of LID, one potential urban stormwater runoff reduction approach, was performed at the watershed scale in this existing urban watershed.

The potential of LID as a component of an urban stream health improvement plan was examined for several storm events by modeling event-based stream flow metrics as %IC was reduced in the Park River Watershed. The results of this assessment demonstrate that LID, modeled as a reduction in %IC, can greatly reduce stormwater runoff and peak flow in an urban watershed if initial %IC can be reduced by more than 20% for the 1-yr storm event. Reducing baseline IC by 20% decreases the average %IC to a range of 0% to 23%IC with resultant %IC in eight of 12 stream sites below the recommended threshold of 12% IC for stream health. Stream hydrology responds to the implementation of LID with multiple sites demonstrating the elimination of runoff for 30% IC reduction. However, LID implementation in such a highly-urbanized watershed is complex. Runoff is not reduced or eliminated at many sites even for a 30% IC reduction for the 1-yr storm event. For this watershed, assessment indicates that factors in addition to contributing area and %IC have a hydrologic impact. The two stream sites located

at confluences have the greatest total and peak flow indicating that stream length may factor into runoff reduction assessment. While IC reduction can be an integral component of a stormwater mitigation plan, the application may be limited in an urbanized setting.

For CSO reduction, the implementation of LID results in a substantial volume reduction. However land use practices in the Park River Watershed, as in many developed urban areas, will limit the amount of IC that can be reduced. If able to achieve a 20% IC reduction in the watershed, runoff reductions of 28, 47, 107, 139, 192, and 233 MG for the 3-month, 1, 5, 10, 25, and 50-yr storms could be attained. Despite this impressive volume reduction, the target problem - CSO alleviation - is not achieved for any of the assessed storm events. This result is problematic since as long as combined sewers continue to overflow, water quality will be adversely affected. Due to urban “hot spots” – locations within a particular subcatchment that will continue to produce millions of gallons of overflow volume, despite increasing the pervious cover, the total elimination of CSOs, even for a 3-month storm, is unlikely unless the duration of the storm is extended to the point where runoff is minimized regardless of LID implementation (USEPA, 2000).

Successful LID implementation is achieved when the LID is confronted by low intensity, smaller storm events. For smaller events, LID is able to perform as designed and retain/treat water where it falls. Decreased stormwater runoff volume, as a result of LID, implies that less grey infrastructure would be necessary which would allow watershed management to minimize financial resources spent as a stormwater management plan is augmented with LID. Adding to the attractiveness of reallocating stormwater management funds, the secondary benefits associated with LID and green infrastructure will also be realized. Due to the high initial IC and the density of the existing urban setting, an IC reduction of 20% or more, the amount necessary

to achieve a CSO reduction benefit in the Park River Watershed, is difficult. In a developing urban area or a more suburban neighborhood, LID could be more easily integrated providing a greater watershed impact. For the Park River Watershed, LID cannot completely alleviate CSOs for any storm event and is therefore not a suitable option for CSO abatement.

To further examine the potential impact of LID in this watershed, a smaller sub-set of the Park River Watershed, the Granby area, was assessed to determine the impact of location and LID type on the volume reduction of stormwater runoff. Model results from the Granby area indicated that the most cost effective LID technology in such a developed watershed is swales and that the ideal location for implementation is, not surprisingly, in the portion of the watershed where the %IC constituted the highest percentage of catchment land cover. The percentage of stormwater reduction using LID is limited in a dense urban setting due to the constraints of predevelopment. In the Granby area, a maximum %IC decrease of 32% is achievable with 100% implementation of a single LID technology. However, transportation requirements and the limitations of implementing pervious solutions on private land limit the amount of potential mitigation from a single LID technology. Utilizing multiple technologies provides a mechanism to maximize runoff mitigation within the necessary constraint of roadway disruption avoidance.

When evaluating the management decision of whether or not to implement LID, a strategy should be employed from a watershed-level perspective based on the prediction of stormwater runoff reduction. While site-specific assessment would be necessary should LID be deemed a stormwater runoff reduction strategy, a general evaluation of the potential reduction is necessary to determine the role for LID in the overall watershed plan and in the selection process for the optimal LID technology. Optimal LID type and location will vary with watershed development pattern and impervious cover distribution. Additionally, watershed characteristics

such as topography and soils as well as factors such as the location and amount of publicly-owned land, the willingness of residents to pay for LID, and transportation requirements will affect LID selection. While individual LID technologies can have a site-scale impact, the entire watershed must be evaluated to assess watershed-level potential and to capture non-site-specific effects.

Assessment at the watershed scale may indicate that stormwater runoff cannot be completely eliminated due to the density of urban development; however, the implementation of LID in an urban setting does contribute to stormwater runoff reduction along with providing additional watershed benefits. The implementation of LID, while unable to completely eliminate runoff from storms larger than the 1-yr storm event, will reduce the amount of stormwater runoff created. For example, if a given LID technology captures 1-in of rainfall from the 10-yr, 24-hr storm (5-inches of precipitation), then the storm event is effectively reduces to a 5-yr, 24-hr storm (4-inches of precipitation; USDA, 1986). This reduction in storm size as perceived by the watershed reduces the runoff and the impact of urbanization allowing for the implementation of less grey infrastructure. LID also provides hydrologic benefit to the watershed by increasing infiltration and therefore improving groundwater recharge. Additionally, LID technologies reintroduce nature into the urban environment resulting in beautification and a visual reminder to the public of the need to conserve and appreciate natural resources.

The results obtained from this study extend the current knowledge surrounding the application of LID as a stormwater BMP in an urban watershed to include an improved understanding of the watershed scale effect of LID implementation. This research determines that IC reductions resulting from the implementation of LID on a watershed scale do not sufficiently reduce stormwater runoff volume to the extent necessary for CSO elimination, but

can reduce the number of active CSOs; improve stream health; and assist in determining the ideal placement of LID in a watershed. As a result of this study, better descriptive data concerning the effectiveness of utilizing LID as a stormwater runoff management strategy in an existing urban watershed is presented. Walsh et al. (2005) stated that the remediation of stormwater impacts is most likely to be achieved through widespread application of innovative approaches to drainage design. This research tested the implementation of LID on a watershed scale to determine the practical extent of the benefits of large scale reduction in impervious cover and provides insight to watershed management about the potential for LID implementation to mitigate or enhance specific urban stormwater runoff concerns. The stormwater reduction results of this research are directly applicable to those in watershed management positions regarding the use of LID as a stormwater mitigation strategy. These results assist watershed managers in their ability to make informed decisions that align with federal stormwater mandates concerning stormwater runoff volume reduction.

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FIGURES

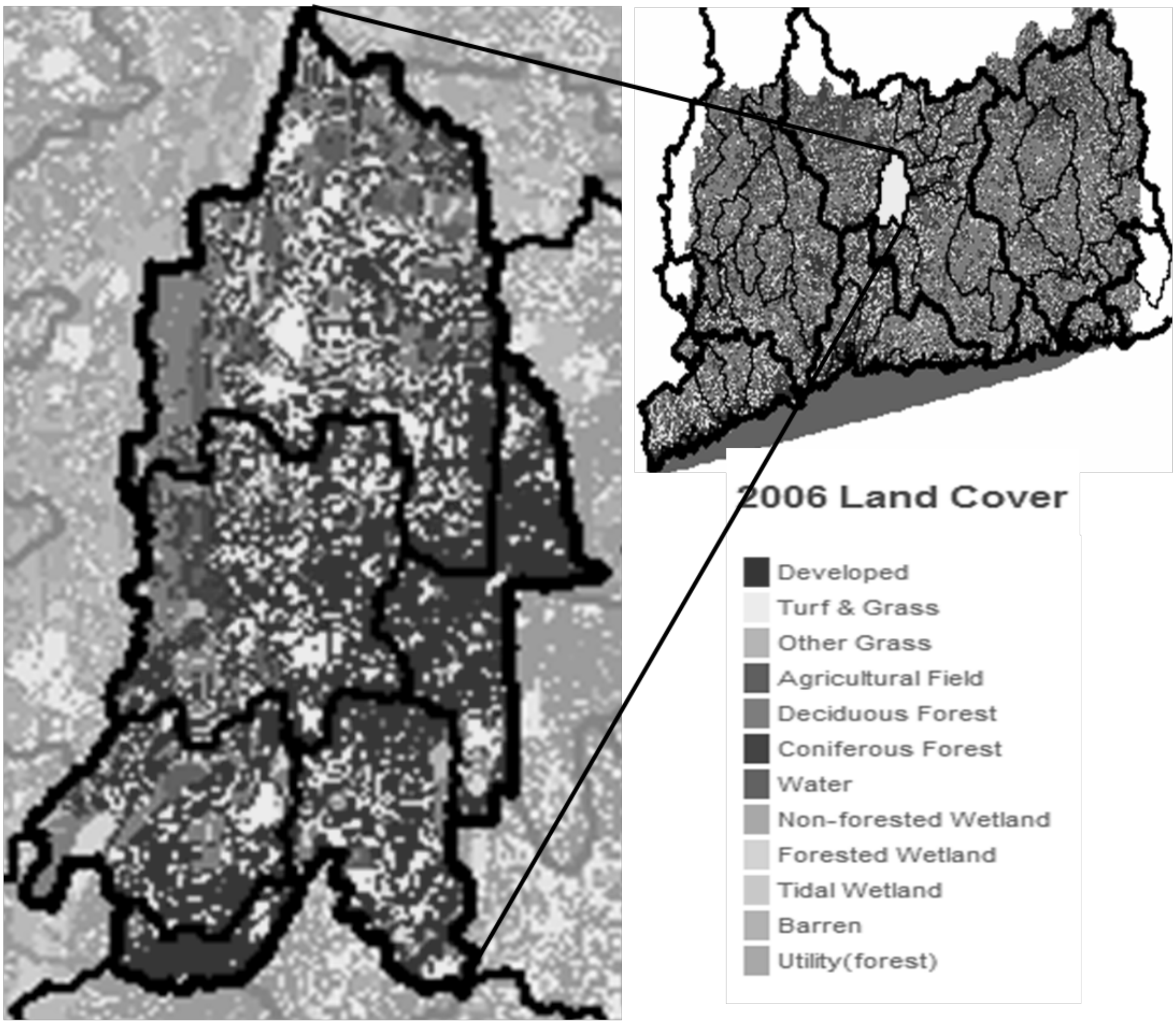


Figure 1. Park River Watershed, CT, USA. The watershed encompasses all or portions of 8 towns: Avon, Bloomfield, Farmington, Hartford, New Britain, Newington, West Hartford and Wethersfield. This 77 square mile watershed is heavily urbanized with an average percent impervious cover of 54.9%. There are 82 CSOs located within the watershed and portions of the stream have been channelized as part of past stormwater management projects.
(Image taken from clear.uconn.edu/projects/landscape)

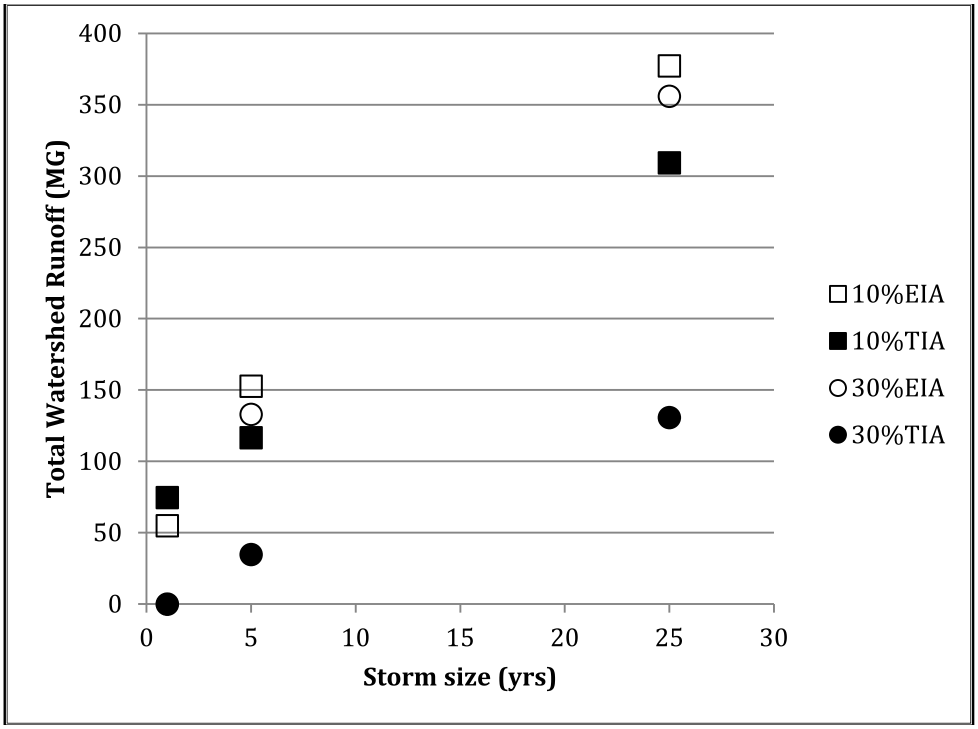
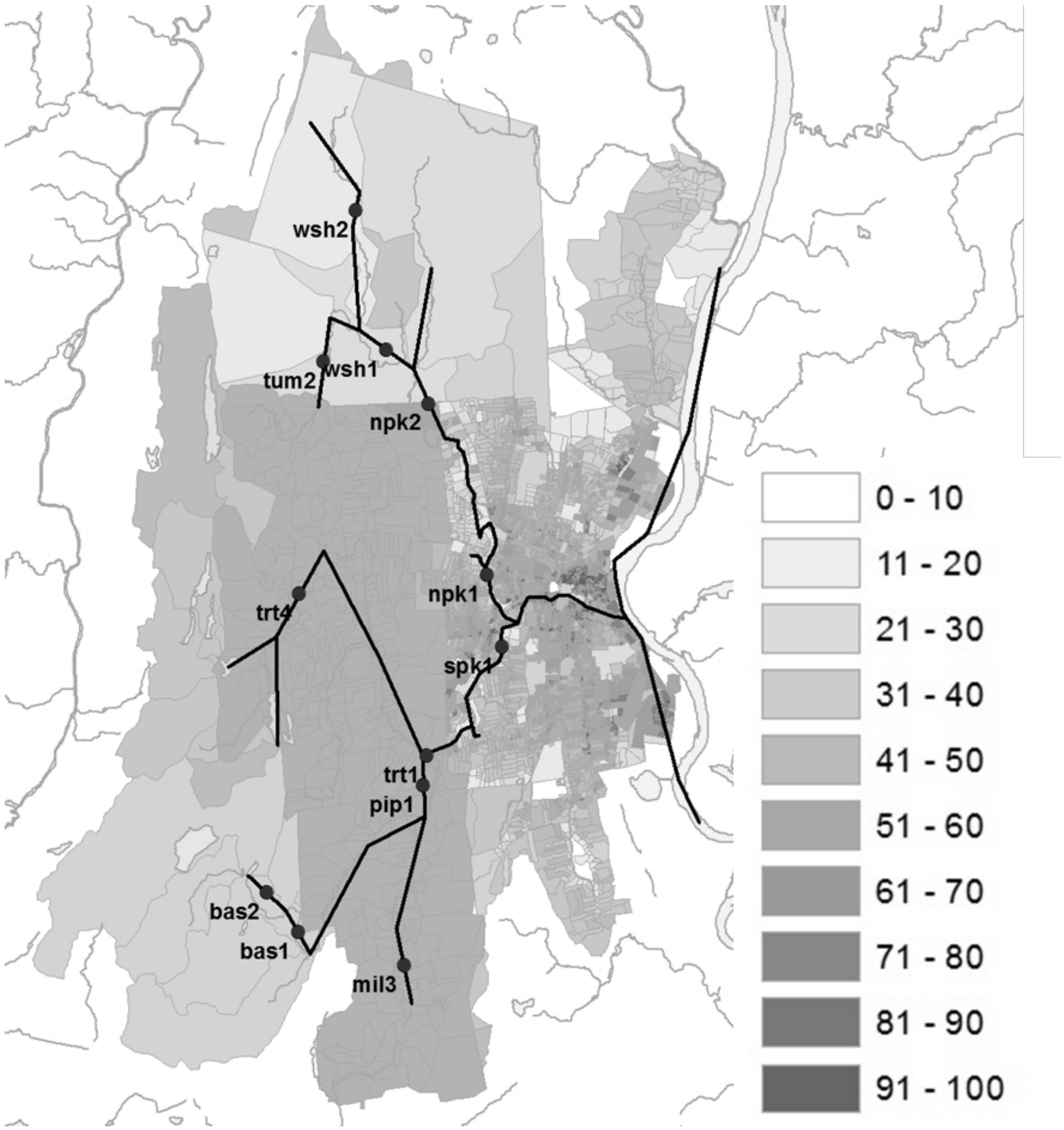


Figure 2. Impact of using effective impervious area (EIA; open symbols) relative to total impervious area (TIA; closed symbols) reductions to represent LID implementation. TIA is defined as the fraction of watershed covered by constructed, non-infiltrating surfaces such as concrete, asphalt and buildings while EIA is defined as the impervious surfaces with direct hydraulic connection to the downstream drainage or stream system (Booth and Jackson, 1997).



(Map courtesy of Shawn King and the University of Connecticut's Center for Land Use Education and Research, http://clear.uconn.edu)

Figure 3. Study area – Park River Watershed located in Hartford, CT, USA. Stream assessment sites indicated on the map of the watershed. Twelve points were selected to highlight the urban gradient within the watershed by comparing points along the streams from headwaters to the watershed outlet. Average %IC of the watershed is shown.

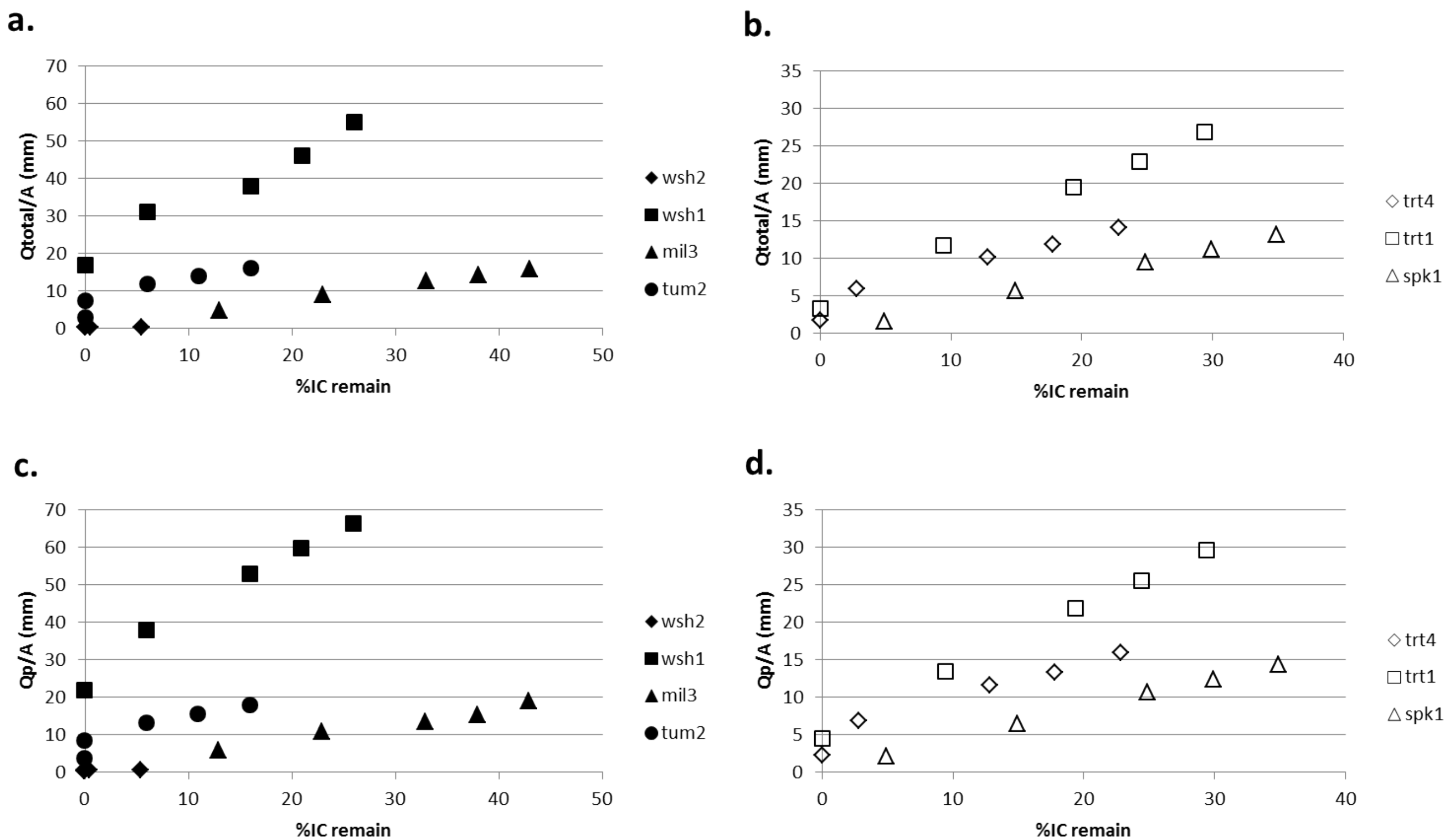


Figure 4 illustrates the decrease in total runoff (Q_{total}) and peak runoff (Q_p), both normalized by contributing area, as %IC remaining decreases across a set of small, similarly sized watersheds with varied initial %IC (a. and b.) and a set of watersheds along an urban gradient (c. and d.) for the 1-yr, 24-hr storm. Figures 2a and 2b: sites *mil3, tum2, wsh1*, and *wsh2*, are all similar in size (1.5, 2.4, 4.7 and 1.7 square miles respectively) with varied initial %IC (43%, 16%, 26% and 6%, respectively). Figures 2c and 2d follow Trout Brook (sites *trt4* and *trt1*) to the South Branch Park River (*spk1*) site and provide an urban gradient.

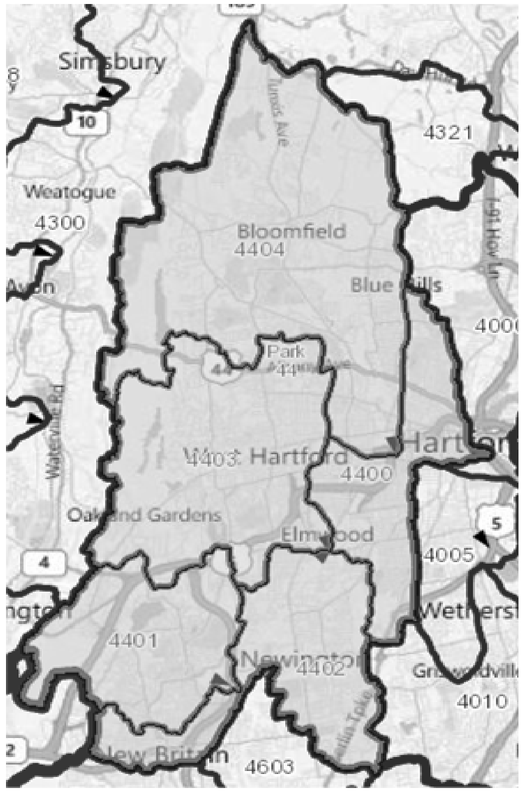


Figure 5. Map of the Park River Watershed, Connecticut.

Figure 6. Location of the Granby watershed in northwest Hartford, CT, USA. The watershed represents a dense, urban watershed bordered approximately by Granby Street, Blue Hills Avenue, the city line and the Westbourne Parkway.

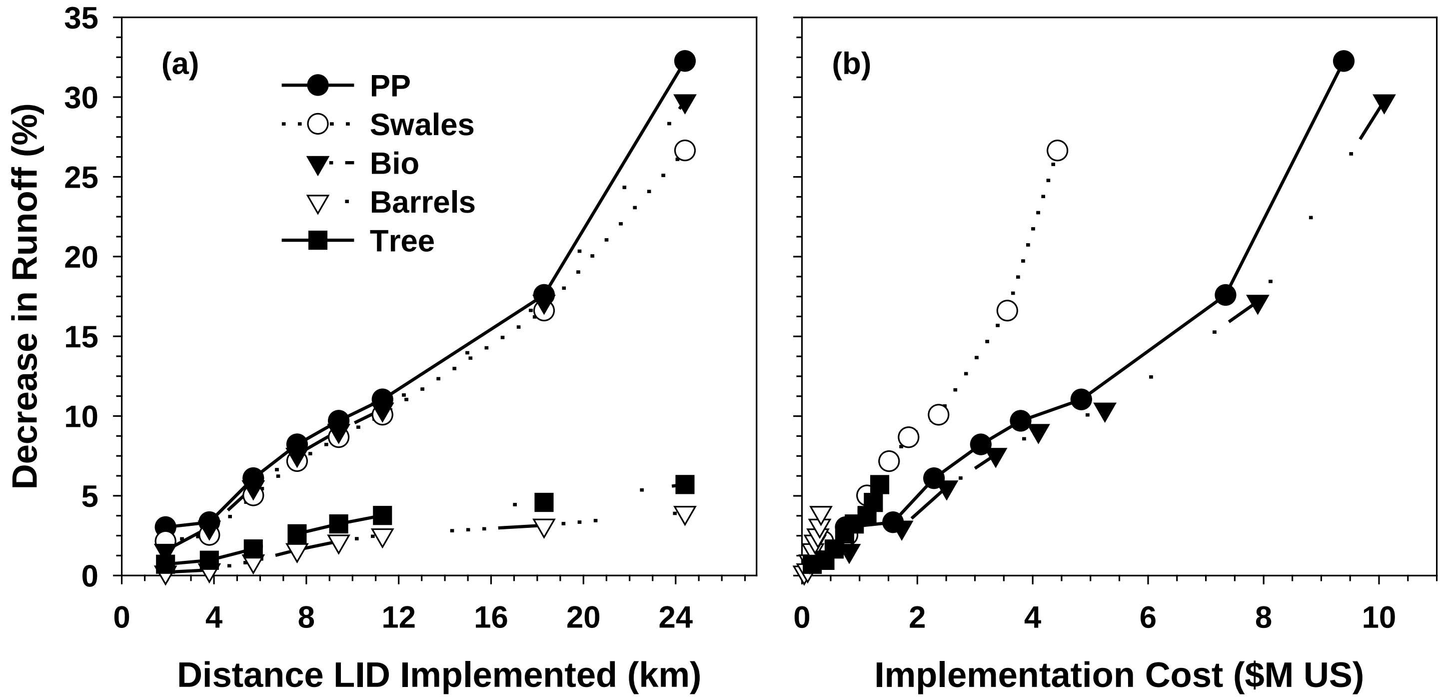


Figure 7 Comparison of percent runoff reduction to implementation distance (a) and cost (b) of low impact development best management practice (BMP). BMPs were implemented as a function of linear roadway distance over 2 km intervals through 12 km and then 75% and 100% of the available roadway. BMPs included roadway (swale, bioretention and porous pavement) and non-roadway (tree boxes and rain barrels) options. Runoff was estimated using a SWMM model constructed and validated for the area for the Metropolitan District Commission. Costs were estimated from averages of published average costs as given in Table 14.

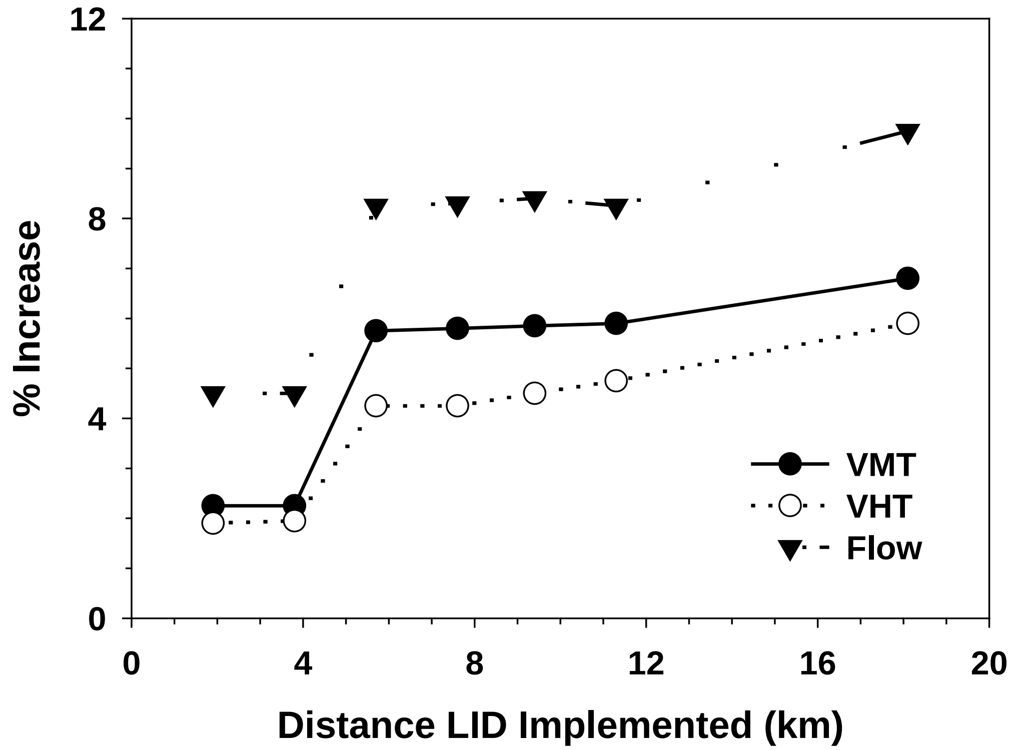


Figure 8 Impact of roadway low impact development BMP implementation on transportation metrics, vehicle miles traveled (VMT), vehicle hours traveled (VHT) and flow. Percent increase evaluated using VISSIM and TransCAD relative to the existing base case. Lines do not reflect trends.

TABLES

Table 1. Characteristics of stream site watersheds, listed from north to south, in the Park River Watershed (Hartford, CT). Average %IC used as a metric of the urban gradient. Two sub-sets representing an urban gradient (#) and a group of similarly-sized (*) watersheds with varied initial %IC were investigated in greater detail as part of this research.

	Site	Contributing Area (km^2)	Average %IC
North Branch Park River	**wsh2***	4.4	6
	wsh1*	12.2	26
	tum2 *	6.22	16
	npk2	59.6	28
	npk1	72.5	30
South Branch Park River	**trt4 #**	14.5	23
	spk1 #	114	35
	trt1 #	53.4	29
	pip1	67.3	39
	bas2	18.6	22
	bas1	33.7	36
	mil3 *	3.88	43

Table 2. Total rainfall (mm) for each simulated precipitation magnitude and intensity modeled using data from Miller et al. (2002), Department of Commerce (1961), Connecticut Stormwater Quality Manual (2004), and MDC (2004).

Duration (hr)	**Return Period (yr)**				
	1	**2**	**5**	**10**	**25**
1	25.4	25.9	32.5	38.9	44.2
6	45.7	56.6	70.9	89.4	118
24	66.0	81.3	119	140	176

Table 3. Total watershed runoff normalized by contributing area (Q_{total}; *mm*) for 12 stream sites for the 1-year storm event. Reduction in %IC was simulated in the model by direct subtraction from the baseline %IC for each subwatershed. Sites arranged by river branch and in order of increasing % initial IC.

IC Reduction (%)	***South Park River***													
	bas2		***trt4***		***trt1***		***spk1***		***bas1***		***pip1***		***mil3***	
	IC (%)	**Runoff (mm)**	**IC (%)**	**Runoff (mm)**	**IC (%)**	**Runoff (mm)**	**IC (%)**	**Runoff (mm)**	**IC (%)**	**Runoff (mm)**	**IC (%)**	**Runoff (mm)**	**IC (%)**	**Runoff (mm)**
0	22	12	23	14	29	27	35	13	36	8	39	7	43	16
5	17	10	18	12	24	23	30	11	31	6	34	6	38	14
10	12	8	13	10	19	20	25	9	26	5	29	5	33	13
20	2	4	3	6	9	12	15	6	16	3	19	2	23	9
30	0	0	0	2	0	3	5	2	6	0	9	0	13	5

IC Reduction (%)	***North Park River***									
	wsh2		***tum2***		***wsh1***		***npk2***		***npk1***	
	IC (%)	**Runoff (mm)**	**IC (%)**	**Runoff (mm)**	**IC (%)**	**Runoff (mm)**	**IC (%)**	**Runoff (mm)**	**IC (%)**	**Runoff (mm)**
0	5.5	0.4	16	16	26	55	28	16	30	15
5	0.5	0.4	11	14	21	46	23	14	25	13
10	0	0.3	6	12	16	38	18	12	20	11
20	0	0.3	0	8	6	31	8	8	10	8
30	0	0.3	0	3	0	17	0	4	0	4

Table 4. Peak flow rate normalized by contributing area ((Q_p; *mm*) for 12 stream sites for the 1-year storm event. Reduction in %IC was simulated in the model by direct subtraction from the baseline %IC for each subwatershed. Sites arranged by river branch and in order of increasing % initial IC.

IC Reduction (%)	***South Park River***													
	bas2		***trt4***		***trt1***		***spk1***		***bas1***		***pip1***		***mil3***	
	IC (%)	**Q_p (mm/d)**	**IC (%)**	**Q_p (mm/d)**	**IC (%)**	**Q_p (mm/d)**	**IC (%)**	**Q_p (mm/d)**	**IC (%)**	**Q_p (mm/d)**	**IC (%)**	**Q_p (mm/d)**	**IC (%)**	**Q_p (mm/d)**
0	22	14	23	16	29	30	35	14	36	9	39	8	43	19
5	17	12	18	13	24	26	30	12	31	7	34	5	38	15
10	12	10	13	12	19	22	25	11	26	6	29	3	33	14
20	2	5	3	7	9	14	15	7	16	3	19	3	23	11
30	0	0	0	2	0	5	5	2	6	0	9	0	13	6

IC Reduction (%)	***North Park River***									
	wsh2		***tum2***		***wsh1***		***npk2***		***npk1***	
	IC (%)	**Q_p (mm/d)**	**IC (%)**	**Q_p (mm/d)**	**IC (%)**	**Q_p (mm/d)**	**IC (%)**	**Q_p (mm/d)**	**IC (%)**	**Q_p (mm/d)**
0	5.5	0.5	16	18	26	66	28	17	30	16
5	0.5	0.5	11	16	21	60	23	15	25	14
10	0	0.5	6	13	16	53	18	13	20	12
20	0	0.4	0	8	6	38	8	9	10	9
30	0	0.4	0	4	0	22	0	4	0	4

Table 5. Storm intensity assessment of area-normalized runoff (Q_{total}; mm) and peak flow rate (Q_p; mm) for the 1-hr, 6-hr and 24-hr durations of the 1-yr storm event at all stream sites under baseline (0% IC reduction) conditions. Further decrease in %IC reduced runoff at each stream site as previously shown. Storm duration trends remained the same as shown here for the 0%IC reduction.

		Storm duration					
		24-hr		**6-hr**		**1-hr**	
Site	***Average %IC***	Q_{total}	Q_p	Q_{total}	Q_p	Q_{total}	Q_p
mil3	*43*	16	19	11	23	5	12
pip1	*39*	7	8	5	13	2	7
bas1	*36*	8	9	5	14	2	8
spk1	*35*	13	14	9	20	4	9
npk1	*30*	15	16	10	25	5	11
trt1	*29*	27	30	18	40	8	18
npk2	*28*	16	17	10	28	5	15
wsh1	*26*	29	34	19	48	9	28
trt4	*23*	14	16	9	27	4	15
bas2	*22*	12	14	8	22	4	13
tum2	*16*	11	13	8	28	4	18
wsh2	*6*	1	1	0	1	0	1

Table 6. Describes the historical storm events used for analysis. "*IC Reductions*" lists storms used to evaluate the effect of implementing IC reductions on overflow volume, the number of active outfalls, and treatability of specific CSO outfalls using LID. "*Storm Intensity*" lists additional 1-year events used to evaluate the effect of storm intensity on volume and number of overflows.

Return Frequency (yr)	Date	Duration (hr)	Intensity (mm/hr)	Total Precipitation (mm)
		IC Reductions		
0.25	27-Jun-83	27	1.5	44
1	10-Apr-83	15	4.1	63
5	19-Aug-91	16	6.4	103
10	19-Aug-55	10	11.4	115
25	18-Aug-55	20	8.9	176
50	18-Aug-55	30	7.6	229
		Storm Intensity		
1	17-Aug-62	7	10.4	72
1	12-Feb-08	25	2.8	71

Table 7. Quantifies the total overflow volume of CSO (in MG) in the Park River Watershed as a function of storm size and LID implementation. Green infrastructure represented as a IC reduction on a total IC basis. Base case is represented by the 0% IC reduction. Data estimated using a SWMM watershed model developed by CDM Smith, Inc.

% IC Reduction	Return Frequency (yr)					
	0.25	**1**	**5**	**10**	**25**	**50**
0	38	74	167	240	383	527
5	31	61	140	191	344	497
10	25	52	117	168	304	448
15	20	45	104	143	272	326
20	10	27	60	101	191	294
30	5	16	35	69	131	240

Table 8. Quantifies the number of active outfalls in the Park River Watershed as a function of storm size and LID implementation. Green infrastructure represented as a IC reduction on a total IC basis. Total number of CSO locations in the watershed is 81. Base case is represented by the 0% IC reduction. Number of outfalls that "*never overflow*" for a given storm size is given by the difference between 81 and the base case (e.g., for the 1-yr return frequency, 81-44 = 37 outfalls never experience overflow). The number of active outfalls which are "*LID Treatable*" is the difference between that level of IC Reduction and the prior level within each respective storm size. For example, for the 1-yr return frequency, 41-38 = 3 additional active outfalls are prevented from overflowing with 10% IC reduction that would have overflowed with only a 5% IC reduction. Data estimated using a SWMM watershed model developed by CDM Smith, Inc.

% IC Reduction	**Return Frequency (yr)**					
	0.25	**1**	**5**	**10**	**25**	**50**
0	42	44	67	76	77	77
5	40	41	63	73	77	77
10	*34*	*38*	*63*	*73*	*77*	*77*
15	29	35	58	71	76	76
20	24	31	47	63	73	74
30	16	21	35	48	61	65

Table 9. Impact of storm intensity on the number of active CSO outfalls. Evaluation performed for a 1-yr return frequency event with characteristics provided in Table 6. The Mid-level intensity represents the base case which was included in the evaluation of LID impact across a range of storm sizes (Table 3). Data estimated using a SWMM watershed model developed by CDM Smith, Inc.

% IC Reduction	Intensity		
	Higher	**Mid (Base)**	**Lower**
0	*78*	*44*	*1*
5	*77*	*41*	*1*
10	*77*	*38*	*1*
15	*77*	*35*	*1*
20	*69*	*31*	*1*
30	*57*	*21*	*1*

Table 10. Stormwater management costs using green and grey infrastructure for the stormwater runoff produced by the 1-yr, 15-hr storm for various IC reductions in the Park River Watershed. A general cost estimate of $0.02 per gal-treated annually for grey infrastructure runoff management (Hazen and Sawyer, 2012) was used. The mid-range cost for conventional stormwater storage was taken from the National Stormwater Management Calculator ($11.55 per cubic foot; CNT, 2009). Grey infrastructure cost estimate values use the volume produced and green infrastructure costs are based on the overflow volume reduced for each IC scenario. For green infrastructure, no specific LID type was identified for this assessment. LID runoff management costs range from $0.02 to $0.18 per gal-treated; therefore, an average cost per gallon treated of $0.11 was used (Hazen and Sawyer, 2012). Total cost of stormwater management is the sum of grey infrastructure, green infrastructure and storage.

IC Reduction	Volume (MG)	Grey Infrastructure ($M/yr)	Stormwater Storage ($M/yr)	Green Infrastructure ($M/yr)	Total Cost ($M/yr)
0	226	4.53	349	0	354
5	183	3.67	283	4.71	292
10	152	3.03	234	8.21	245
15	125	2.51	194	11.1	207
20	68	1.37	105	17.4	124
30	36	0.71	54.9	21.0	76.6

Table 11. Low impact development best management practices (BMPs) considered in the Granby watershed in Hartford, CT. BMPs were separated into those impacting road right-of-way and those not implemented on roadways. LID options were implemented as a function of roadway distance of in 2 km increments through 50% of the watershed roadway as well as 75% and 100% of the 24.4 km of roadways in the watershed.

	LID Type	Design Variables		Design Reference
Roadway		***Width (m)***	***Length (m)***	
	Bioretention [a]	2.7	12.2	CASQA, 2003; Prince George's County, 2007
	Swales [b]	2.44	15	Blick et al., 2004
	Porous Pavement [c]	3.05	Varies by implementation distance	Legret and Colandini, 1999; Houle, 2008
Non-Roadway		***Size***	***Spacing***	
	Tree Boxes	3.34 m^2	recommended 30.5 m apart	Virginia Department of Conservation, 1999
	Rain Barrels [d]	590 L	1 per house in implementation area	USEPA, 2011(a)

[a] Area per feature = 33.4m2. Recommended sizing of 4.6 m by 12.2 m cannot be attained given watershed restrictions. Implemented bioretention does meet all mandated design criteria.

[b] Area per feature = 37.2 m2. A width of 2.44 m was selected based on the recommended minimum design slope of 3.

[c] The implemented width is the width of a parking lane, 3.05 m. Length is the total length of roadway selected.

[d] An average roof area was estimated to be 158 m^2 based on aerial photographs. It was assumed that each barrel drains half the roof.

Table 12. SWMM LID design criteria for porous pavement (PP), vegetative swales (Swale), bioretention basins (Bio), rain barrels (RB), and tree boxes (TB). Vegetation volume fraction is the storage depth filled by vegetation. Very dense growth value of 0.2. Surface roughness given by Manning's *n* (Rough concrete - 0.03; short grass pasture, no brush - 0.25; flood plains, heavy brush - 0.075). Surface slope of LID feature assumed to be 0 for Bio/TB and 1 for PP/Swale. Slope should not exceed 2.5%. Assume entire implementable area pervious for PP. Drain coefficient is zero if no underdrain. NA – not applicable.

	Process Layer	PP	Swale	Bio	RB	TB
Surface	Storage depth (in)	0[1]	12[2,3]	3[2]	NA	12[4]
	Vegetation Volume Fraction	0	0.1	0.15	NA	0.15
	Surface Roughness	0.03	0.25	0.075	NA	0.075
	Surface slope (%)	1	1	0	NA	0
	Swale side slope	NA	3[2]	NA	NA	NA
Pavement	Thickness (in)	6[5]	NA	NA	NA	NA
	Void Ratio (-)	0.175[5]	NA	NA	NA	NA
	Impervious Surface Fraction	0	NA	NA	NA	NA
	Permeability (in/hr)	340[5]	NA	NA	NA	NA
	Clogging Factor	0	NA	NA	NA	NA
Storage	Heigth (in)	12	NA	12	51	12
	Void Ratio (-)	0.75	NA	0.75	NA	0.75
	Conductivity (in/hr)	10	NA	10	NA	10
	Clogging Factor	0	NA	0	NA	0
Underdrain	Drain coefficient (in/hr)	0	NA	0	0	0
	Drain exponent	0.5	NA	0.5	0.5	0.5
	Drain offset height (in)	0	NA	0	0	0
	Drain delay (hrs)	NA	NA	NA	6	NA
Soil	Thickness (in)	NA	NA	48[2]	NA	24[6]
	Porosity (vol fraction)	NA	NA	0.5	NA	0.5
	Field Capacity (vol fraction)	NA	NA	0.2	NA	0.2
	Wilting Point (vol fraction)	NA	NA	0.08	NA	0.1
	Conductivity (in/hr)	NA	NA	0.5	NA	0.5
	Conductivity slope	NA	NA	10	NA	10
	Suction head (in)	NA	NA	3.5[6]	NA	3.5[6]

[1] ISUIT, 2009
[2] CASQA, 2003
[3] Blick et al., 2004
[4] Portland SW Manual, 2005
[5] PCA, 2004
[6] Prince George’s Country, 2007

Table 13. Street implementation lengths for LID evaluation. Length given for each street (in km) under a given coverage scenario.

	Total Coverage Within Watershed (km)					
Street	**2**	**4**	**6**	**8**	**10**	**12**
Garfield	0.18		0.18	0.18	0.18	0.18
Burlington		0.48	0.48	0.48	0.48	0.48
Sharon		0.50	0.50	0.50	0.50	0.50
Hebron		0.52	0.52	0.52	0.52	0.52
Chatham		0.57	0.57	0.57	0.57	0.57
Plainfield			0.60	0.60	0.60	0.60
Thomaston			0.64	0.64	0.64	0.64
Pembroke				0.69	0.69	0.69
Colebrook				0.78	0.78	0.78
Andover	0.84				0.84	0.84
Westminster						0.88
Branford						0.90
Manchester						0.92
Tower					0.94	0.94
Canaan						
Pomfret				0.19	0.19	0.19
Litchfield				0.41	0.41	0.41
Durham			0.42	0.42	0.42	0.42
Simpson		0.32	0.32	0.32	0.32	0.32
Harold		0.71	0.71	0.71	0.71	0.71
Burnham	0.93	0.93	0.93	0.93	0.93	0.93
Lyme						
Palm						
Hartland						
Cornwall						
Salisbury						
Holcomb						
Granby						
Westbourne						
Blue Hills						

Table 14. Cost estimates for low impact best management practices (BMPs) evaluated. Average costs were estimated from published values in the literature.

LID Technology	**Cost ID**	**Cost**	**Unit**	***Reference***
Porous Pavement (PP)	Implemented	$128.09	per m^2	*Dreyer, 2012*
	Low	*$5.38*	*per* m^2	*LIDC, 2005*
	High	*$124.86*	*per* m^2	*USEPA, 2011a*
Swale	Implemented	$82.45	per m^2	*USEPA, 2011*
	Low	*$3.23*	*per* m^2	*RRDP, 2001*
	High	*$82.00*	*per m length*	*USEPA, 2000*
Bioretention	Implemented	$161.46	per m^2	*USEPA, 2011*
	Low	*$32.29*	*per* m^2	*USEPA, 2000*
	High	*$430.56*	*per* m^2	*LIDC, 2005*
Rain Barrel	Implemented	$2,500.00	per barrel	*CICEET, 2007*
Tree Box	Implemented	$195.00	per box	*USEPA, 2011a*

SUPPLEMENTAL INFORMATION:

Table SI.1 24-hr storm event data for each storm assessed.

Site	Storm size (yr)	*0%IC reduction* %IC remain	*0%IC reduction* Q total (m^3)	*5% IC reduction* %IC remain	*5% IC reduction* Q total (m^3)	*10% IC reduction* %IC remain	*10% IC reduction* Q total (m^3)	*20% IC reduction* %IC remain	*20% IC reduction* Q total (m^3)
bas1	1	36	253000	31	214000	26	174000	16	88000
bas1	2	36	345000	31	292000	26	237000	16	121000
bas1	5	36	424000	31	358000	26	290000	16	147000
bas1	10	36	532000	31	448000	26	362000	16	183000
bas1	25	36	744000	31	626000	26	504000	16	255000
bas2	1	22	226000	17	192000	12	156000	2	80000
bas2	2	22	312000	17	263000	12	213000	2	108000
bas2	5	22	382000	17	323000	12	261000	2	132000
bas2	10	22	480000	17	404000	12	326000	2	165000
bas2	25	22	673000	17	565000	12	456000	2	230000
mil3	1	43	60000	38	56000	33	49000	23	35000
mil3	2	43	86000	38	78000	33	69000	23	49000
mil3	5	43	107000	38	96000	33	85000	23	60000
mil3	10	43	136000	38	122000	33	107000	23	75000
mil3	25	43	195000	38	174000	33	152000	23	106000
npk1	1	30	1086000	25	957000	20	827000	10	558000
npk1	2	30	1485000	25	1309000	20	1129000	10	760000
npk1	5	30	1819000	25	1601000	20	1381000	10	927000
npk1	10	30	2278000	25	2003000	20	1726000	10	1156000
npk1	25	30	3218000	25	2819000	20	2423000	10	1618000

Table SI.1 24-hr storm event data for each storm assessed (cont).

Site	Storm size (yr)	*0%IC reduction*		*5% IC reduction*		*10% IC reduction*		*20% IC reduction*	
		%IC remain	**Q total (m^3)**	**%IC remain**	**Q total (m^3)**	**%IC remain**	**Q total (m^3)**	**%IC remain**	**Q total (m^3)**
npk2	1	28	949000	23	828000	18	712000	8	477000
npk2	2	28	1288000	23	1132000	18	973000	8	646000
npk2	5	28	1578000	23	1385000	18	1189000	8	789000
npk2	10	28	1976000	23	1733000	18	1486000	8	984000
npk2	25	28	2792000	23	2440000	18	2088000	8	1377000
pip1	1	39	464000	34	395000	29	320000	19	159000
pip1	2	39	641000	34	540000	29	436000	19	220000
pip1	5	39	786000	34	661000	29	531000	19	269000
pip1	10	39	984000	34	826000	29	666000	19	336000
pip1	25	39	1376000	34	1041000	29	928000	19	467000
spk1	1	35	1520000	30	1282000	25	1086000	15	653000
spk1	2	35	2070000	30	1762000	25	1491000	15	884000
spk1	5	35	2545000	30	2164000	25	1830000	15	1082000
spk1	10	35	3211000	30	2727000	25	2305000	15	1363000
spk1	25	35	4580000	30	3884000	25	3282000	15	1950000
trt1	1	29	1439000	24	1226000	19	1042000	9	627000
trt1	2	29	1977000	24	1687000	19	1432000	9	853000
trt1	5	29	2433000	24	2072000	19	1757000	9	1044000
trt1	10	29	3070000	24	2613000	19	2214000	9	1315000
trt1	25	29	4379000	24	3723000	19	3154000	9	1882000

Table SI.1 24-hr storm event data for each storm assessed (cont).

Site	Storm size (yr)	*0%IC reduction*		*5% IC reduction*		*10% IC reduction*		*20% IC reduction*	
		%IC remain	**Q total (m^3)**	**%IC remain**	**Q total (m^3)**	**%IC remain**	**Q total (m^3)**	**%IC remain**	**Q total (m^3)**
trt4	1	23	203000	18	171000	13	148000	3	87000
trt4	2	23	280000	18	234000	13	202000	3	120000
trt4	5	23	344000	18	287000	13	247000	3	146000
trt4	10	23	431000	18	359000	13	309000	3	182000
trt4	25	23	632000	18	525000	13	451000	3	267000
tum2	1	16	348000	11	828000	6	712000	0	195000
tum2	2	16	1288000	11	1132000	6	973000	0	646000
tum2	5	16	1578000	11	1385000	6	1189000	0	789000
tum2	10	16	1976000	11	1733000	6	1486000	0	984000
tum2	25	16	2792000	11	2440000	6	2088000	0	1377000
wsh1	1	26	3000	21	4000	16	5000	6	3000
wsh1	2	26	5000	21	5000	16	6000	6	6000
wsh1	5	26	6000	21	6000	16	6000	6	6000
wsh1	10	26	7000	21	7000	16	7000	6	7000
wsh1	25	26	8000	21	10000	16	10000	6	10000
wsh2	1	6	71000	1	63000	0	53000	0	33000
wsh2	2	6	98000	1	85000	0	72000	0	46000
wsh2	5	6	119000	1	103000	0	87000	0	55000
wsh2	10	6	148000	1	128000	0	109000	0	69000
wsh2	25	6	206000	1	179000	0	151000	0	95000

APPENDIX

An evaluation of the dynamics of N loading and source contributions in an urban CSS

INTRODUCTION

Combined sewer systems (CSSs), which collect both stormwater and sanitary waste, are present in over 770 cities throughout the United States and result in approximately 40,000 overflow events each year (Belling et al., 2002). When these CSSs overflow during large storm events, termed combined sewer overflows (CSOs), stormwater along with untreated wastewater containing toxins, pathogens and both human and industrial waste are directed into nearby water bodies (Soonthomnonda and Christensen, 2008; Gasperi et al., 2006; Gromaire et al., 2001). CSOs occur when the sewer system is overwhelmed by the influx of stormwater runoff during a precipitation event and consequently is delivered to nearby receiving waters (USEPA, 1995). Because of the pollutants present, CSOs adversely affect the water quality when they enter a water body and are considered a primary contributor to water pollution (USEPA, 2004).

Given the negative environmental impacts of CSSs, municipalities have recognized the need for improved stormwater management strategies and are searching for ways to eliminate aging CSSs (USEPA, 2009; NRC, 2008; MDC, 2007). The most common management strategy is to separate the CSS into two separate systems: a stormwater system and a sewer system. However, the separation of CSSs and the development of systems designed to alleviate runoff from expanding impervious cover (IC) represent costly management decisions and system separation plans typically do not include a management plan for the capture and treatment of the remaining stormwater runoff (USEPA, 1999). The issues surrounding CSOs will continue to worsen as development escalates, increasing surface runoff as well as raw sewage input and

further stressing engineered systems (Grimm et al., 2008). Simultaneously, climate change will produce more extreme precipitation patterns potentially leading to longer dry deposition periods and heightened peak runoff (Semadeni-Davies et al., 2008; Kaushal et al., 2008).

Of the numerous pollutants introduced during a CSO, the addition of nitrogen (N) is of particular concern due to its potential to enhance the development of anoxia and eutrophication, both of which challenge municipalities with difficult management decisions (CTDEEP, 2010; NYSDEC and CTDEP, 2000). The evaluation of N loading, including its timing and potential bioavailability, and the impact of CSOs on receiving water quality, are issues facing many municipalities, particularly those within the northeastern United States (NRC, 2008; CTDEEP, 2005). To combat the negative environmental impacts and reduce N from stormwater runoff and CSOs, various conventional systems (i.e. sewer separation, and ponds) and alternative source control measures (i.e. permeable pavement, bioretention, wetlands and vegetated swales) can be considered (Collins et al., 2010). Understanding the speciation of N delivery during CSO events, as well as the effect of potential management strategies, is critical in developing cost-effective approaches and minimizing negative environmental impacts.

The goal of this modeling effort is to provide urban watershed management professionals with improved CSS modification data through the assessment of two common stormwater management strategies and to examine the resulting implementation effect of each strategy on N loading to the stream and water pollution control facility (WPCF). To quantify the total N loading, watershed hydrology and the CSS is modeled using the Environmental Protection Agency’s Stormwater Management Model (SWMM). By modeling the estimated annual N loading in SWMM, the potential benefits of two common, distinct stormwater management strategies - separated systems and low impact development (LID) - is assessed to determine the

impact of each strategy in terms of N loading to the receiving water body. The two primary N contributing sources from CSOs, sewage and stormwater runoff, will contribute to each overflow event allowing the N loading from the CSO to the stream and to the WPCF to be quantified. Modeling the system, both as it exists now, a combined system, and as separated system, measures the effectiveness of separation. Given the EPA's recent directive to include LID as a stormwater mitigation practice, various degrees of LID implementation are also assessed to determine the N loading reduction possible through impervious cover reduction (USEPA, 2010). To evaluate the potential benefit of each management strategy in terms of N loading reduction, separate model simulations were evaluated for complete sewer separation without LID implementation and for no system separation with two LID implementation scenarios (10% and 30%). The ultimate N loading from the sewershed (CSOs plus WPCF) is then used to assess the impact of each management strategy on N reduction.

In many developed areas (e.g., Hartford), a strong impetus to separate the sewage and runoff systems exists due to certainty of design, experience with traditional methods, and the mandate to remedy the situation or face fines (Fuss and O'Neill, 2010; MDC, 2007). However, the potential implications of sewer separation without concomitant stormwater treatment are uncertain. Grey infrastructure approaches utilized by municipalities only address the CSO challenge, in many situations ignoring the potential implications of the resultant stormwater volume and associated contaminant load. Understanding the potential changes in contaminant loading to the stream and WPCF, particularly with regard to N, due to CSS separation or LID implementation is important for informing management decisions, especially in light of the separate regulatory silos for WPCF effluent, CSOs and stormwater.

LITERATURE REVIEW

N in Urban Waters

Characteristics of the urban environment like increased impervious cover, reduced vegetation, channelization of streams and degradation of wetlands and riparian zones can greatly reduce urban watershed N retention functions particularly during stormflow conditions (Collins et al., 2010). As a consequence of reduced N retention, contributions of N to receiving waters in an urban environment are increased (Taylor et al., 2005; Seitzinger et al., 2002, Gromaire et al., 2001). The primary constituents of N that contribute to N pollution depend on the type of stormwater/sewage system implemented. In the presence of a CSS, where stormwater is combined with sewage, four main species of N can be expected. Sewage contributes reduced species of N – ammonia N (NH_3) and organic N (OrgN) which combine to form total Kjeldahl Nitrogen (TKN) while stormwater runoff contributes oxidized species of N - nitrite (NO_2^-) and nitrate (NO_3^-) (Taylor et al., 2005; Brezonik and Stadelmann, 2002, Sztruhar et al., 2002). Of these expected N loading contributors, the dissolved inorganic N (DIN) components (NH_3, NO_2^- and NO_3^-) have the greatest impact on water bodies because they are readily mobilized and available for uptake by simple organisms (Galloway et al., 2003; Seitzinger et al., 2002; Sztruhar et al., 2002). DIN pollution typically leads to eutrophication, hypoxia and loss of biodiversity (Taylor et al., 2005). Nitrate, NO_3^-, is often the most common soluble species in aquatic systems and urban runoff and is not well retained by soil particles (Galloway et al., 2003). High NO_3^- concentrations in receiving waters can indicate general urban impacts while high NH_3 concentrations indicate anaerobic conditions or organic pollutants from sewers (Taylor et al., 2005). Kaushal et al. (2008) quantified NO_3^- flux and speciation within stream water in Maryland reporting that the NO_3^- export constituted a larger fraction of total N export within urban areas,

increasing from 0.03-0.2 kg ha^{-1} yr^{-1} within a forested reference watershed to 2.9-15.3 kg ha^{-1} yr^{-1} within the suburban/urban streams of Baltimore, MD demonstrating the significant impact of impervious surfaces on N flux.

Urban N Reduction Management Strategies

Reducing N loading to urban streams has become a focal point of urban watershed management especially in areas where CSSs exist. As populations move toward urban centers, resulting in an expansion of the built environment, the quantity of IC is increased which results in the inability of urban watersheds to retain N and has, therefore, increased the likelihood of N pollution from urban stormwater runoff. To reduce the impact of contamination by CSSs, many municipalities have already, or are planning to, complete projects that result in total separation of stormwater and municipal wastewater sewer systems (USEPA, 1999). Traditional engineering approaches such as sewer separation and underground storage are used to eliminate or reduce CSO events while stormwater retention ponds have been used to reduce stormwater runoff (Konrad and Booth, 2005; Lloyd et al., 2002). Conventionally, stormwater has been managed using urban water infrastructure, nicknamed “grey infrastructure”, which includes a network of pipes and storage basins designed to facilitate sewer separation, underground storage and increased treatment plant capacity (Hazen & Sawyer, 2012).

As an alternative to grey infrastructure, current approaches to stormwater management are beginning to incorporate LID and site design that stresses infiltration and the reduction of impervious surfaces (USEPA, 2010; Pitt and Clark, 2008; Grumbles, 2007). LID utilizes predominantly natural processes such as infiltration and evapotranspiration to manage storm flows by mimicking the predevelopment hydrologic regime (Pitt and Clark, 2008). The benefits

of LID have been shown to reduce or even eliminate runoff in short-term, small scale storms (Hazen & Sawyer, 2012; Garrison and Hobbs, 2011). However, as the length and intensity of the storm increases, the effectiveness of LID decreases. Larger storms produce an inordinate amount of runoff volume, resulting in significant flooding. Although LID cannot prevent flooding, the volume of runoff may be reduced resulting in a decrease in the pollutant loading to receiving waters (Garrison and Hobbs, 2011). As a management strategy, the goal of LID is to decrease peak flow and the volume of stormwater discharged into storm drains and water bodies following precipitation events (Dietz, 2007). Current research also reveals that several LID alternative stormwater control measures, such as bioretention, filters and wetlands show greater promise in their ability to remove N from stormwater than more conventional practices (Collins et al., 2010; Li and Davis, 2009; Passeport et al., 2009; Walsh et al., 2009; Kaushal et al., 2008; Dietz, 2007; Davis, 2005). Furthermore, LID and green infrastructure are the preferred approaches by EPA and the CT DEEP for stormwater management in urban and suburban areas (USEPA, 2010; Fuss and O'Neill, 2010).

Modeling N Flux in SWMM

For this assessment, the latest version of the United States Environmental Protection Agency's Stormwater Management Model (SWMM; version 5.0.022, released in April 2011) which simulates hydrology, hydraulics and water quality of urbanized watersheds was used (USEPA, 2011). SWMM is a widely used model that has been applied to sewer and stormwater studies throughout the world (Singh and Frevert, 2006). This particular version of SWMM has been applied to urban areas to evaluate stream flows and pollutant loads base on an average year of rainfall (ENSR, 2006).

SWMM is a dynamic rainfall-runoff and hydraulic simulation engine that was designed to predict the resultant runoff in urban areas from each modeled subcatchment in response to precipitation input (USEPA, 2011). SWMM is a physically based, deterministic model that simulates water inflows, outflows and storages within a subcatchment. A water balance equation is solved at every time step to update the depth of water over a subcatchment and the depth of surface runoff is calculated using Manning's equation. SWMM tracks the quantity and quality of water in each pipe and channel for each time step during a simulation (Rossman, 2010).

The SWMM platform is used to estimate the pollutant loads associated with runoff and sewage for this assessment. While research has shown that water quality predictions in SWMM have higher uncertainty than water quantity predictions, SWMM has been shown to have an average prediction error of less than 20% for various pollutant loads (Baffaut and Delleur, 1990; Tsihrintzis and Hamid, 1998; Jewell et al., 1978). Chiew and McMahon (1999) have also shown that water quality characteristics can vary considerably between catchments and, in the absence of specific data, models can only provide a guide to the probably range of diffuse pollution loading generated from a catchment. For this assessment of a large urban watershed, specific catchment data is not available. To gain a broad understanding of the potential ability of different management strategies in terms of N reduction, a prediction error of less than 20% has been deemed acceptable. Final modeling results will be compared to field collected data when possible to verify that the prediction error is indeed less than 20%.

Runoff pollutants can be simulated in SWMM through the buildup and washoff parameters over various land uses or input as concentrations in rainfall, groundwater, direct infiltration/inflow, and dry weather flow (Rossman, 2010). Dry weather pollutant buildup within a land use category can occur in SWMM as either a mass per unit of subcatchment area or per

unit of curb length and the amount of buildup is a function of antecedent dry weather days (Rossman, 2010). Pollutant washoff is simulated using user-defined land use categories during wet weather periods through the use of exponential, rating curve or event mean concentration functions (Rossman, 2010).

Representative Year

While the use of a long-term precipitation record will provide the most accurate rainfall-runoff simulation results, model simulations over multiple years require extensive run time and are therefore impractical and often unnecessary (Tsay et al., 2007). A typical rainfall period must represent trends – overall depth, distribution of storm events, intensity variations - present in the long term period of record. For this simulation, a “representative year” of precipitation data was run to span the range of potential events. After evaluating 47 years (1955-2001) of complete hourly data from Bradley International Airport, the Metropolitan District Commission (MDC) in the city of Hartford, CT, working with consultants, selected 1976 as a “representative year” of precipitation. The 1976 record of precipitation events is presented in Table 1A. In 1976, many small storms occurred, but nothing larger than the 1-yr storm event. Given climate change predictions, storm intensity definitions are shifting. However, for consistency with the MDC, calendar year 1976 was used as a “representative year” for this evaluation. By simulating the representative year in the model, an estimation of the annual loading of N from both sewage and stormwater entering the stream via the stormwater system and from the WPCF can be determined. As is practice, the loading estimate from the “representative year” can then be utilized to obtain an estimated annual loading.

SUMMARY

To quantify the potential reduction in N loading from stormwater runoff to urban streams due to the implementation of various management strategies, two LID implementation scenarios are assessed and compared along with the standard sewer separation, grey solution relative to the base case – the case in which no modifications are made to the existing urban environment. The dynamics of N loading across individual CSO discharge events and within the CSS are modeled to provide a comprehensive assessment of the delivery of N species to nearby waterways and to the WPCF. The quantity of each contributing N source to the urban stream is determined through the assignment of N loading values to both stormwater and sewage and determined for each assessment scenario using hydrological modeling.

Prior to performing any hydrological modeling, N speciation and loading was assigned for each contributing N pollutant source in the model. For sewage, the inflow into the dry weather flow (DWF) was modified for each node in the sewer system. Based on sewage data collected in the watershed, average N concentrations of 0.07 mg/L, 9.49 mg/L and 6.13 mg/L were input for nitrites and nitrates ($NO_{x)}$, organic nitrogen (OrgN) and ammonia (NH_3) respectively. Based on previous data collected in the watershed, these values were reasonable. For most watersheds, sewage will be predominantly total Kjeldal nitrogen (TKN; a combination of OrgN and NH_3) and be strongest in OrgN (Gasperi et al., 2010; Sztruhar et al., 2002). The flow within the sewer system was not altered as the model was previously calibrated based on the hydrology of the watershed. The time patterns for the established flow were used to modify the N concentration of each constituent within the system. To model the N loading created by stormwater runoff, pollutants were added under the quality menu. TKN and NO_x were added for each catchment in the catchment editor under the initial buildup function. Since dissolved N forms, typically NO_x,

tend to dominate urban runoff, only NO_x and TKN were modeled for runoff (Taylor et al., 2005; Sztruhar et al., 2002). It was assumed that both pervious and impervious land cover would contribute N to the watershed therefore in the Land Use Editor, buildup and washoff functions were created for both NO_x and TKN for pervious and impervious land uses.

Once SWMM was populated with N data, several runs were performed to assess N loading and speciation changes due to modifications based on selected management strategy options. Each model scenario was run for the representative year (1976) to ensure uniformity in terms of time and precipitation. A baseline scenario, where no changes were made to the existing model, was first conducted. Using this baseline, overflow data from each CSO was collected along with annual flow and N speciation data for the CSS pipe just prior to the CSO for each CSO in the model.

To evaluate the potential benefits of a separated system, the flow and N data for the baseline scenario (stormwater plus sewage) in the CSS pipe just prior to each CSO was compared to a "dry" scenario. The "dry" scenario was calculated by running the model for the representative year in the absence of any precipitation and assessing the conduit in the CSS just prior to the CSO to determine the N loading and flow contributions of the sewage for the year. By removing the sewage contribution from the baseline scenario, stormwater runoff contributions to flow and N loading were determined. This assessment was done to quantify the stormwater runoff contributions to the watershed that would be present if sewer separation were performed. In the case of sewer separation, the sewage would be retained within the CSS and flow directly to the WPCF altering the input to the WPCF. The stormwater runoff would not enter the CSS, but instead, flow directly to receiving water bodies.

To evaluate the potential benefits of LID implementation, two LID scenarios are implemented and compared to the baseline CSO contributions. LID implementation is simulated by reducing the percent impervious cover (%IC) in the model using the EIA IC reduction method. Reductions in %IC of 10% and 30% were evaluated to assess a mid-range LID implementation and a maximum level LID implementation for the watershed. Each LID management strategy is used to calculate the N contribution to the watershed from the volume of combined stormwater and sewage that is produced in the scenario. The flow and N loading entering the watershed from the CSOs under the baseline scenario is compared with the same metrics from the two LID implementation scenarios. By identifying the location of the CSO's in the model, the overflow contribution to the stream for each scenario for the representative year is determined. The individual N loading from each CSO location is calculated and summed to produce an estimated N loading from the watershed to the Connecticut River during the representative year.

In addition to N loading to the stream from CSOs, N loading to and from the water pollution control facility (WPCF) is a concern. An estimation of N loading to the WPCF is accomplished by assessing flow in the CSS as it enters the plant. The input conduit into the WPCF provides the flow and associated N loading. During a precipitation event, sewage and stormwater runoff combine in the CSS and some of the combined wastewaters will be released via CSO while the remainder of the combined waters will flow to the WPCF through the system. The processing of N through the WPCF is calculated by comparing the N loading entering the WPCF with the plant outlet. Actual N loading data from the outlet has been collected and will be compared to the estimated load leaving the facility.

In the Park River watershed, strategies are being developed to reduce N discharge from the WPCF. Because the total maximum daily load (TDML) limits and manages the overall N loading from point sources (i.e., WPCFs) to Long Island Sound, the point sources in the watershed have been the focus of the management strategies (CTDEEP, 2003). The drawback to this approach is that N loading from non-point sources such as stormwater runoff is not taken into consideration. The aim of management is to achieve the goals of the Long Island Sound Study, the comprehensive Conservation and Management Plan and the state's General Permit for the discharge of N in which CT must bring down the average concentration of N in WPCF discharges down to a state-wide average of 5.6-mg/L by 2014 (MDC, 2012). While point source reduction has been proven to achieve N reduction from WPCFs to receiving waters, a management strategy solely focused on point source reduction does not fully capture the changes in N loading to the watershed as a result of a selected management strategy. An understanding of N delivery to the stream from the CSOs, the stormwater system discharge and the WPCF is important.

FUTURE WORK

The combination of the outfall from the WPCF and the CSO data for the year quantifies the amount of stormwater runoff that can be expected to enter the urban steam. In the separate systems, the flow into the WPCF will be just sewage and is determined by assessing the flow in the conduit just prior to the WPCF in SWMM in the absence of a rain event.

The MDC has implemented a tunnel capture system for CSOs followed by treatment. This presumably will be effective at removing the N going into the WPCF … discuss relative to the impact on stormwater N loading that will still be captured and treated.

- Show for smaller events, when CSOs wouldn't overflow, N loading from runoff would be captured, but when system is separated this N will enter WS – *quantify this value from data*
- Need to compare approximate costs for sewer separation vs. tunnel vs. LID
    - Use a $/gal alleviated value from USEPA
    - Divide by the total load and show as $/kg N removed.
- Ease of implementation for the given scenarios. Link with the cost above, the ability of The MDC to implement the strategy (public vs. private), and the disruption to the public during implementation.

TABLES

Table 1A. Total Precipitation Events for 1976

Storm count	Event type
3	1yr
1	6month
3	3month
4	2 month
3	1 month
15	3 week
2	2 week