Journal of Environmental Management 171 (2016) 81–91

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Modeling flood reduction effects of low impact development at a watershed scale

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ARTICLE INFO

Article history:
Received 1 June 2015
Received in revised form
26 January 2016
Accepted 28 January 2016
Available online 13 February 2016

Keywords:
Urban growth
Storm runoff
Modeling
PCSWMM

ABSTRACT

Low impact development (LID) is a land development approach that seeks to mimic a site's pre-development hydrology. This study is a case study that assessed flood reduction capabilities of large-scale adoption of LID practices in an urban watershed in central Illinois using the Personal Computer Storm Water Management Model (PCSWMM). Two flood metrics based on runoff discharge were developed to determine action flood (43 m^3/s) and major flood (95 m^3/s). Four land use scenarios for urban growth were evaluated to determine the impacts of urbanization on runoff and flooding. Flood attenuation effects of porous pavement, rain barrel, and rain garden at various application levels were also evaluated as retrofitting technologies in the study watershed over a period of 30 years. Simulation results indicated that increase in urban land use from 50 to 94% between 1992 and 2030 increased average annual runoff and flood events by more than 30%, suggesting that urbanization without sound management would increase flood risks. The various implementation levels of the three LID practices resulted in 3–47% runoff reduction in the study watershed. Flood flow events that include action floods and major floods were also reduced by 0–40%, indicating that LID practices can be used to mitigate flood risk in urban watersheds. The study provides an insight into flood management with LID practices in existing urban areas.

1. Introduction

Conversion of natural landscapes to residential, commercial, and industrial land uses has long been identified as a major contributor to environmental and hydrological changes (e.g., Shuster et al., 2005; Gunn et al., 2012; O'Driscoll et al., 2013; Roy et al., 2014). Hydrological implications of urbanization are typically translated through alteration of natural water systems such as increasing runoff rate and volume, decreasing infiltration and groundwater recharge (e.g., Brun and Band, 2000; Wang et al., 2003; Brandes et al., 2005), increasing temperature, habitat modification (Leopold, 1968; Rose and Peters, 2001; Konrad and Booth, 2002, 2014), and increasing flood risks (Konrad, 2014), leading to water quality degradation (USGS, 1999; Rose and Peters, 2001; Konrad and Booth, 2002). Impervious surfaces with directly connected storm drainage systems generally lead to elevated proportions of rainfall being converted into runoff that flows into receiving waters, resulting in higher and flashier flood events (Hollis, 1974, 1975; Konrad, 2014). Studies reported that the effects of urbanization on watershed hydrology are more noticeable for small and moderate storms following dry periods (Hollis, 1975; Konrad, 2014) as frequent and large rainstorms could balance the difference in imperviousness characteristics between urban and rural catchments (Martens, 1968; Hollis, 1975; Tang et al., 2005).

Management of stormwater with directly connected curbs, gutters and pipe conveyance systems has gained less popularity in recent years with the emergence of alternative water sensitive land development and design techniques that control stormwater at the source such as low impact development (LID) (PGCo, 1999a, b; USEPA, 2000; Coffman, 2002; Moglen et al., 2003). Low impact development practices include essentially distributed stormwater control measures (e.g., permeable pavement, bioretention systems, and vegetated swales), which seek to mimic natural hydrologic functions through retention, infiltration, evaporation, and recycle of stormwater on-site (Dietz, 2007; Davis et al., 2009; Ahiablame et al., 2012). The adoption and benefits of LID practices have been substantially documented in the scientific literature (e.g., USEPA,

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http://dx.doi.org/10.1016/j.jenvman.2016.01.036
0301-4797/

2000; Dietz, 2007; Scholz and Grabowiecki, 2007; Berndtsson, 2010).

Credits given to the hydrological impacts of LID practices have largely been directed toward management of storm runoff peak, runoff volume, and water quality. For example, Bedan and Clausen (2009) reported that post-development runoff was reduced by 42% and peak discharge was similar to that of the pre-development peak in a watershed with LID practices in Waterford, Connecticut. The most commonly adopted LID practices include green roof, swale, rain barrel (RB), bioretention/rain garden (RG), and porous pavement (PP), with the latter three being the focus of this study. Implementation of LID pavement (i.e., PP) at various geographic locations showed reduction in runoff volume and associated pollutant loads through interception, filtration, sedimentation, transformation of nutrients, and removal by microorganisms (e.g., Dietz, 2007; Tota-Maharaj and Scholz, 2010; Ahiablame et al., 2012). Field measurements showed that PP on parking lots can reduce runoff volume by 50–93%, and related pollutant loads by more than 75% (e.g., Rushton, 2001; Dreelin et al., 2006). The use of RBs and cisterns has also been shown to reduce runoff volumes and pollutant loads (Walsh et al., 2014; Ahiablame et al., 2013; Jennings et al., 2013), like the case of RB adoption in the District of Columbia and Township of North Huron, Ontario, which resulted in 12% and 5% capture of storm runoff, respectively, flowing into to the sewer systems (Trieu et al., 2001; IBC, 2011). Bioretention systems have been recognized efficient in promoting infiltration, evapotranspiration, groundwater recharge, and pollutant load reduction in addition to reduction of runoff volumes and peak flows (e.g. Davis et al., 2009; Ahiablame et al., 2012). When implemented as retrofitting technologies on existing parking areas, RGs were shown to reduce runoff volumes and peak flow rates by 97% and 99%, respectively (e.g., DeBusk and Wynn, 2011; Hunt et al., 2008), and pollutant concentrations by 30–60% (Hunt et al., 2008).

Even though there is a widespread recognition that LID practices can be effectively used for storm runoff management, their flood control capability is not well understood, especially at large scales. Earlier work on urban flood management with LID was typically geared toward design storms and event-based flood management in relatively small watersheds (Qin et al., 2013). In addition, there is currently a scarcity of quantitative information that documents large scale and long-term adoption of LID practices as retrofitting technologies for flood management in urban watersheds. The goal of this study was to demonstrate through a case study the use of LID practices to reduce flooding in an urban watershed located in central Illinois. The specific objectives were to (1) examine the impacts of urbanization on storm runoff and flooding; and (2) evaluate the potential effectiveness of LID practices for flood mitigation in the study watershed. Various scenarios of urban area increase and LID implementation were evaluated in the study watershed using the Personal Computer Storm Water Management Model (PCSWMM). This study hopes to provide an elaborated view to support municipalities and metropolitan districts in their efforts to manage urban flooding and combined sewer overflows.

2. Materials and methods

2.1. Study area

The City of Normal-Sugar Creek Watershed (HUC 071300090701), located in McLean County in Central Illinois (Fig. 1) was selected as the study watershed. This watershed was chosen because of the high proportion of urban land use in the watershed and appropriate data available for conducting the modeling exercise. With a total drainage area of 87.6 km^2, the watershed has one rain observation station (Bloomington Waterworks) and one streamflow gage station (Sugar Creek near Bloomington, IL; BMII2), which is located at its outlet (Fig. 1). Based on the National Land Cover Database (NLDC) 2006 (NLDC, 2006; Fry et al., 2011), more than 80% of the watershed area is urbanized, with two major cities – Bloomington and Normal (Illinois) (Fig. 2). In this study, the City of Normal-Sugar Creek Watershed is referred to as the Sugar Creek Watershed (SCW).

2.2. Data used

Daily and hourly rainfall data were used for runoff and flood risk estimation in this study. Thirty years of daily rainfall data (January 1, 1984 to December 31, 2013) were obtained from Bloomington Waterworks station (Fig. 1). There were no hourly rainfall data at this station so 26 years of hourly rainfall data, from January 1, 1987 to December 31, 2012, were obtained from the nearest rain gage station (Fairbury Waterworks), located northeast within 50 km of the centroid of the watershed. Average monthly evaporation data (1971–2000) for the watershed were extracted from the National Weather Service Climate Prediction Center database (http://www.cpc.ncep.noaa.gov/soilmst/e.shtml).

Thirty years of streamflow data were obtained from the Sugar Creek streamflow gage station near Bloomington, IL (BMII2; USGS 05580950) (Fig. 1), and the Web-based Hydrograph Analysis Tool (WHAT; Lim et al., 2005) was used to separate runoff from daily streamflow. The WHAT system uses three methods for baseflow separation; these include the local minimum method, one-parameter digital filter, and two-parameter digital filter or Eckhardt filter (Lim et al., 2005). The Eckhardt filter was used in this study as it was previously validated for watersheds with characteristics similar to the SCW.

Land use maps for 1992, 2001 and 2006 were extracted from NLCD (Homer et al., 2007; Fry et al., 2011). A predicted land use map for 2030 was extracted from outputs of the Land Transformation Model (LTM) developed by Pijanowski et al. (1997, 2000, 2002a). The LTM uses geographic information systems, artificial neural networks, geostatistical and remote sensing technologies to forecast land use change and assess the spatial and temporal aspects of driving forces of land use change (Pijanowski et al., 1997, 2000, 2002a). Through machine learning and pattern recognition, the model trains on past NLCD land use data for various periods to determine urbanization patterns and construct land use projections (Pijanowski et al., 1997, 2000, 2002a). The outputs of the model are provided as ArcGIS grid files, which can be directly ingested into a hydrologic model. The LTM has been shown to provide accurate predictions for NLCD land use data in the Midwest United States (Pijanowski et al., 2002b, 2014), and widely used in environmental impacts of land use change studies (e.g., Wayland et al., 2002; Tang et al., 2005; Pijanowski et al., 2005; Mishra et al., 2010).

All the land uses were reclassified as high intensity (developed high intensity and developed medium intensity land uses), low intensity (developed open space and developed low intensity land uses), grass (grassland/herbaceous and pasture/hay land uses), forest/woods (deciduous forest and evergreen forest), agricultural (cultivated crops), water/wetland (open water, woody wetlands and emergent herbaceous wetlands), and bare land (bare rock, bare sand, and bare clay). Based on the four land use maps, land use change that would occur between 1992 and 2030 in the watershed was estimated with ArcGIS. In 1992, approximately 50% of the total watershed area was urban (i.e., low and high intensity; Table 1). This proportion increased to 80%, 83% and 94% in 2001, 2006 and 2030, respectively (Table 1; Fig. 2). The 2006 land cover was used as the base case for model calibration and validation.

To determine the proper amount of runoff that would enter the urban drainage collection system, the percent of directly connected