Evaluation of Land-use, Climate change, and Low Impact Development Practices on Urban Flooding

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Abstract

We investigated the potential influence of land-use and climate change on urban hydrology for an urbanized watershed located in Columbia, South Carolina (USA). The Personal Computer Storm Water Management Model (PCSWMM) was used as an urban hydrology model to formulate the low impact development (LID) controls on runoff for flood mitigation. We used ensemble projections provided by the North American Regional Climate Change Assessment Program (NARCCAP) for the climate change assessment. The results for future periods (2038-2069) show an increase in mean annual runoff from 40% to 70%. The LID mitigation strategies were compared based on the rain barrel, rain garden, and a combination of both approaches to evaluate the potential reduction in urban flooding. It is recommended that LID practices should be used synergistically with improved drainage facilities for successful stormwater management. This analysis will help stakeholders to develop strategies to minimize the socio-economic impacts due to urban flooding.
Keywords: PCSWMM, LID, Climate change, Urban flooding

1. Introduction

Due to the rapid population growth and other external factors like technological development and social reforms, urbanization in the USA has increased significantly. Since 1910, there has been nearly 500% growth in the urban population, while the rural population has grown by 19% (Hobbs and Stoops, 2002). The urban population percentage was 75.3% and 82.3% for the years 1990 and 2018, respectively, and it is expected to reach 89.2% in 2050 (UN-DESA, 2018). Urbanization occurs due to the conversion of natural landscapes to developed land for residential, commercial, or industrial purposes (Ahiablame and Shakya, 2016; Roy et al., 2008). Urbanization increases imperviousness cover, and as a result, it decreases infiltration and increases stormwater runoff compared to natural or pervious surfaces (Harbor, 1994; Seth and Norman, 2001). Besides, the amount of sediment washed into stream exacerbates the impacts on water quality (Hall et al., 1999; Ren et al., 2003; Tu, 2011) and causes pollution, thus harming the ecosystem and natural habitat of aquatic animals and plants (Chadwick et al., 2006; McKinney, 2008; Seto et al., 2012). Various stormwater management facilities are typically designed based on the historical streamflow data, assuming that the future climate will remain stationary. The future stormwater runoff characteristics (e.g., peak flow) may not exceed the recorded information. However, climate change is likely to impact extreme precipitation characteristics (i.e., intensity, duration, and frequency), including Intensity-Duration-Frequency (IDF) curves widely used to design civil infrastructure systems (Mishra and Singh, 2010; Vu and Mishra, 2019; Konapala et al., 2020).

Urbanization and climate change likely to alter the urban hydrologic processes (e.g., higher runoff, lower infiltration). Willuweit et al. (2016) applied Dynamic Urban Water Simulation Model to Dublin city in Ireland to explore the urban runoff pattern under changing urban growth and climate scenarios. It was observed that the combined effect of climate and land-use change could potentially increase the monthly runoff by about 57%. Zahmatkesh et al. (2014) used precipitation projections from Intergovernmental Panel on Climate Change (IPCC) Coupled Model Intercomparison Project (CMIP5) in a New York City watershed. They concluded a substantial increase in future urban runoff volume and peak flow rate. In a study by Waters et al.

(2003), climate change contributed to the rise in the total runoff volume by 19% for a small urban catchment in Ontario using Global Climate Model (GCM) simulations. Overall, these studies have shown that the effects of climate change on watersheds may vary. When coupled with urbanization, the two factors can operate synergistically, increasing stormwater runoff magnitude (Pyke et al., 2011).

The increase in runoff due to urbanization has been well documented. In a recent study, Akhter and Hewa (2016) predicted a 50% and 320% increase in the mean annual runoff by increasing urbanization percentage by 10% and 70% for Myponga Catchment in South Australia respectively. Ahiablame and Shakya (2016) projected a 63% increase in the runoff between 1992 to 2050 in the City of Normal-Sugar Creek Watershed in Central Illinois. Similarly, Yan and Edwards (2012) studied three different watersheds in Arkansas and identified that between 1993 to 2019, there was an average increase of flood peak discharge by about 178%. Huong and Pathirana (2013) reported a rise in the overall runoff by 21% due to a 55% increase in urban areas. A study conducted by Bhaduri et al. (2001) revealed that for a 10% increase in imperviousness, the annual average runoff increased by 10%.

A variety of concepts have been developed over time to mitigate the increasing amount of urban runoff. For example, Low Impact Development (LID) focuses on local treatment, retention, re-use, infiltration, and conveyance of excess runoff with an overall goal to preserve the pre-development hydrology of a site (Prince George’s County, 1999). As opposed to conventional stormwater management techniques, LID uses cost-effective and straightforward techniques (e.g., rain-garden and green roof) that are not limited to protecting the watershed and maintaining its hydrological regime. The implementation of LID structures has proven to offer a more sustainable solution to stormwater management at both site-scale and watershed-scale (Roy et al., 2008; Lee et al., 2012; Guan et al., 2015). Previous studies have shown promising results for both individual and combination of LID controls like porous/pervious pavements (Legret and Colandini, 1999; Ahiablame and Shakya, 2016), bioretention areas, and rain gardens (Dietz and Clausen, 2005; Davis, 2008), rain barrels (Abi et al., 2009; Jones and Hunt, 2010), grass swales (Abida and Sabourin, 2006; Stagge et al., 2012) and vegetative roofs (Carter and Rasmussen, 2006; Carter and Jackson, 2007) among many others. Many studies have been conducted to examine the performance of LID for improving stormwater management (Davis, 2008; Line et al., 2012; Trieu et al., 2001; Steffen et al., 2013). Multiple studies by Davis (2008), Line et al. (2012), Chapman and Horner (2010), and DeBusk and Wynn (2011) reported up to 58%, 49%, 74%, and 97% reduction in the runoff after the use of Bioretention areas, respectively. The LID techniques impact water flows, but water volume reduction is minimal in extreme events and sensitive to local conditions, such as size and duration of the rainfall event, soil material, and texture (Zhou 2014).

The rainfall inputs for model development used in previous studies are derived based on different assumptions for climate change impact assessment. For example, Gill et al. (2007) used projected rainfall inputs from a stochastic weather generator model. They assumed the projected rainfall is based on the 99th percentile of these stochastic model outputs. Pyke et al. (2011) applied the Change Factor approach (CFs) to assume that the precipitation likely to increase/decrease uniformly 20%. Zahmetkesh et al. (2015) used the Change Factor approach, which is to add a change factor (Delta) to the observation data (to create a dummy time series) and considered that the projected climate data. These rainfall inputs do not adequately represent future climate change scenarios, as they are simulated from the observed data sets. It is important to highlight that the spatio-temporal rainfall information plays a vital role in climate change impact assessment. It should be appropriately included during the model building processes (Maraun et al., 2010). To overcome such limitations, we used the dynamically downscaled climate data from Regional Climate Models from NARCCAP, which can adequately capture the projected climate change scenarios.

This study provides a comprehensive analysis of the potential impact of Land-use, Climate change, and Low Impact Development Practices on Urban Flooding. Besides, this study area was significantly affected by the most severe extreme flooding event during the 1st week of October 2015. The extreme rainfall event associated with this historical flooding event was considered a 1-in-1000-year event (Feaster et al., 2015; Vu and Mishra, 2019) is included in the model development. Different land use and meteorological forcing scenarios obtained from dynamical downscaled Global Climate Models are evaluated in this study. This study's main objective is to investigate the sensitivity of stormwater runoff based on the historical and projected land-use and climate change scenarios in an urban watershed. This study also aims to evaluate LID practices that are used to mitigate the runoff at a watershed scale. The specific objectives are to (a) develop a well-calibrated stormwater management model for an urban watershed using a rainfall-runoff simulation model PCSWMM; (b) quantify the changes in runoff due to various land-use and climate change scenarios; and (c) to evaluate the effectiveness of two primary LID practices (rain garden and rain barrels) in reducing runoff. This study seeks to help water resource managers make informed decisions that aim to minimize stormwater runoff significantly.

The concept of socio-hydrology is an emerging topic (Di Baldassarre et al., 2015; Pande and Sivapalan, 2016), which has gained significant attention in recent decades. This study highlights that the urban flood risk mitigation measures can be a useful tool for socio-hydrology. For example, a robust policy can be implemented to control density regulations, zoning, ecosystem zones, and adequate stormwater retention ponds to ensure flood water is adequately controlled.

2. Study area and methodology

2.1. Study Area

The study area comprises two sub-watersheds located in the state of South Carolina in the United States. These two sub-watersheds are the Upper Congaree River (80%) and Outlet Saluda River (20%) that cover an area of 138 km^2 (Figure 1). The Digital Elevation Model (DEM) was obtained from Light Detection and Ranging remote sensing (LiDAR) at a resolution of 3m from the South Carolina Department of Natural Resources (SCDNR). This study area is characterized by a variety of land cover types, including forests and cultivated land. Most of the study area is developed with large-lot family housing units. The eastern part of the study area consists of the highly developed downtown Columbia region with a mixture of park, residential, and commercial areas. From the year 1992 to 2011, there was a 24% increase in an urban area (Figure 2), and a detailed description of the percentage of watershed areas for urban, non-urban, and wetlands are tabulated in Table 1. On the contrary, the forest and the agricultural regions decreased by 45% and 97%. This study area was significantly affected by the flooding during the historical extreme rainfall event during the 1st week of October 2015. This extreme rainfall event can be considered as a 1-in-1000-year event (Feaster et al., 2015; Vu and Mishra, 2019).

2.2. Hydro-meteorological datasets

Daily average streamflow data were obtained from the USGS website for three stations (US02168504, US02169000, and US02169500) located in the study area (Figure 1). The stations US02168504 and US02169500 were treated as inflow and outflow boundary conditions, respectively, in model development. The data available for the station US02169500 was used for model calibration and validation. According to our calculation, the relative contribution of inlet station US02168504 is about 28% of the outlet station US02169500. The streamflow hydrograph's base flow component was separated using a Web-based Hydrograph Analysis Tool (WHAT) (Lim et al., 2005). Precipitation data was obtained from the National Oceanic and Atmospheric Administration (NOAA) and was verified using data from the PRISM Climate Group (http://www.prism.oregonstate.edu/). The rain gauge station (ID: USW00053867) is located about 12km southeast of the basin centroid (Figure 1). Similar studies by Cantone and Schmidt (2011), Broekhuizen et al. (2019), and Lee et al. (2018) also using one representative rainfall station for the urban region. Average monthly evaporation data were collected from the National Weather Services - Climate Prediction Center. Land-use maps were taken from National Land Cover Dataset (NLCD) for 1992, 2001, 2006, and 2011. The land-use was reclassified (Figure 2) as High Intensity (medium intensity land-use), Low Intensity (open space and developed low-intensity land-use), Grass/Pasture (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 Barren Land (bare rock, bare sand, and bare clay). This was used to calculate each sub-catchment percentage imperviousness using NOAA's Impervious Surface Analysis Tool (ISAT) using an ESRI ArcGIS Pro platform. Population data were obtained from the United States Census Bureau in the form of TIGER/Line shapefiles.

2.3. Projected land-use maps

To simulate the climate change impact on local water resources management, we predicted the land-use map for the year 2050 using the best fit curve approach. We assume that the land-use map-projected for the year 2050 can correspond to the future climate change scenarios for 2038-

2069. First, the scatter plot between the percentage of *urban* areas from NLCD 1992, 2001, 2006, 2011, and a best-fit curve was constructed. It is assumed that urbanization in the year 2050 would follow a similar statistical pattern based on the best fit curve. The best fit curve implies an upward trend in urbanization, having the total urban area for 2050 is 80% (as opposed to 68% in 2011), indicating an urban area of 120 km^2. Subsequently, a land-use map of the projected year 2050 has been constructed based on 2011. The analysis was done using ESRI ArcGIS Pro, and the critical parameters were defined as land-use, slope, and road proximity (Kumar and Shaikh, 2013). Grid & Raster Editor tool available in ArcGIS Pro was used to manually change the pixel values from forest or agricultural land to urban landscaping.

2.4. Stormwater runoff modeling: PCSWMM and model sensitivity analysis

USEPA Storm Water Management Model (SWMM) is a computer program that simulates dynamic rainfall-runoff for a single event and long-term (continuous or period-of-record) runoff quantity and quality (James et al., 2005). Personal Computer Storm Water Management Model (PCSWMM) is a proprietary stormwater modeling software that integrates the SWMM computational engine with a geographic information system (GIS). For the model development, PCSWMM version 7.1.2480 from Computational Hydraulics International company (CHI) was used. Using DEM from SCDNR, the PCSWMM's Watershed Delineation Tool (WDT) was run to delineate sub-catchments (Figure 1). The WDT tool works similarly to other watershed delineation tools, except it uses the concept of target sub-catchment size rather than a minimum area for channelization. Based on the flow direction, slope and contributing area layers were generated for each sub-catchment. Lastly, the streams and flow path layers are created, which show the stream networks and their direction. The streams and flow path layers are used to develop the Conduits layer, which is a key element to represent channels that move water from one node to another in the conveyance system in PCSWMM. To represent the Conduits layer's irregular cross-section, a Transect object is used to define how depth varies with the distance across the cross-section. Transects are created using Transect Creator and Transect Editor tools, which use the elevation data from the provided DEM layer. Other input parameters used in the Conduits layer are Manning’s roughness, inlet and outlet node inverts, and length.

The watershed was divided into 106 sub-catchments, 7473 nodes, and 7950 links (Figure 1) to adequately represent the land-uses, topography, and drainage pattern of the watershed. The stormwater management infrastructures (pipes, gutters, swales, catch basins, etc.) were not considered in this model. It was assumed that these structures' stormwater would eventually drain to the natural flow paths (Abdul-Aziz and Al-Amin, 2016). The model simulated surface runoff at each sub-catchment, node, and link was calculated. The SWMM model has long been used in various urban hydrology prediction and management (Tsihrintzis and Hamid, 1998; Jang et al., 2007; Li et al., 2010). In this study, a sensitivity analysis was performed to determine the model-sensitive parameters after assigning user-defined uncertainty values (or ranks) for each parameter (see the Appendix, Table A1). The range of uncertainty values was derived from “Rules for Responsible Modeling” (James, 2003). The available data record is 16 years (1st January 2000 to 31st December 2015) on a daily scale. The model was calibrated using the Sensitivity-based Radio Tuning Calibration (SRTC) tool for ten years (1st January 2006 to 31st December 2015) and validated for six years (1st January 2000 to 31st December 2005). The daily rainfall data from NOAA and land-use data from NLCD 2011 were used for model calibration and validation. The average daily runoff obtained from the model was compared to runoff values of daily flow from USGS station 02169000. The model performance was evaluated using the Nash-Sutcliffe

Efficiency (NSE) coefficient and coefficient of determination (R^2) values for both daily and monthly scales.

2.5. SWMM LID modeling

In SWMM, a combination of vertical layers is used to represent LID controls. Each layer's properties are defined on a per-unit-area basis, allowing them to be implemented in multiple sub-catchments of different sizes. Evaporation, infiltration, runoff, and water storage through each layer are tracked by performing a moisture balance. In this study, two LID elements (rain garden and rain barrel) were used. In PCSWMM, a rain garden is represented using a combination of surface, soil, storage, and drain parameters (see the Appendix, Table A2, Figure A1). A rain barrel is represented using only storage and drain parameters (see the Appendix, Table A3, Figure A1). The surface overflow of the LID components was directed back to the sub-catchment, and flow from the underdrain was directed into the outlet of the sub-catchment. It was also assumed that there are no clogging issues and no underdrain. The number of rain garden units was determined according to the sub-catchment impervious cover. For a rain barrel case, each one was assumed to have a capacity of 350 liters and was 1.2 m tall and 1.5 cm in diameter (Ahiablame and Shakya, 2016). It was set up to receive 50% of runoff from the roof, and draining time was assigned 6 hours (see the Appendix, Table A3). The number of rain barrels was calculated using the population data and by assuming a homogeneous population density.

2.6. Climate projections from NARCCAP

This study assesses the impact of climate change on local water resource allocation using the ensemble output from the Regional Climate Modeling (RCM) of the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al., 2012). Phase II of NARCCAP utilized the boundary conditions from four different Atmosphere-Ocean Global Climate Models (AOGCMs) and six different RCMs. The simulations were run for baseline climate 1968-1999 and the climate projection 2038-2069 forced using the Special Report on Emissions Scenarios A2 scenario (SRES). According to the fourth assessment report (AR4) of IPCC (2007), the SRES A2 scenario is referred to a very heterogeneous world of continuity increasing population and regionally oriented economic development with slow economic growth and technological change to preserve local identities. A total of 12 pairs of AOGCMs and RCMs are formed in NARCCAP, followed by a balanced statistical design. Similar to Kim et al. (2017), this study selects a sub-set of five pairs of AOGCMs-RCMs that can provide the best ensemble study for climate change impact over South Carolina. The acronyms of selected GCM/RCM and five chosen pairs for NARCCAP models are tabulated in Table 2.

The NARCCAP model outputs provide 3-hourly interval precipitation data over a spatial resolution of 50km for the North American region. Even though dynamical downscaling data produces a finer resolution compared to driving GCMs, there still exists the model bias for each of the RCM. To remove these precipitation biases from RCMs, the non-parametric quantile mapping approach (or distribution mapping) was used. According to Teutschbein and Seibert (2012), the quantile mapping approach is the best bias correction method for both precipitation and temperature variables. This approach has been used in various RCM bias correction studies. The formulation for the quantile mapping approach is shown in equation (1) for a given precipitation time series "x" for a particular month:

$$\tilde{x}_{mc} = F_{oc}^{-1}\left[F_{mc}\left(x_{mc}\right)\right] \quad (1)$$

In which: $\tilde{x}$ is the bias-corrected precipitation. F is the fitting function (in this case: gamma distribution), and F^{-1} is the inverse of the fitting function; '*o*' and '*m*' stand for 'observed' and 'modeled' with the '*c*' is 'current' climate. Equation (1) was used to correct the bias between the observed and climate model at the baseline period. For climate projection, the equidistance quantile mapping approach is applied as shown in equation (2) with the information from observation and climate model at baseline and future period (Vu et al., 2017a; Srivastav et al. 2014; Mirhosseini et al. 2013; Li et al., 2010):

$$\tilde{x}_{mp} = x_{mp} + F_{oc}^{-1}\left[F_{mp}\left(x_{mp}\right)\right] - F_{mc}^{-1}\left[F_{mp}\left(x_{mp}\right)\right] \tag{2}$$

In which denote '*p*' stands for 'projected.'

2.7. Scenario analysis

Different scenarios were investigated to evaluate the potential impact of the projected climate and land cover change by using calibrated hydrologic model PCSWMM. Scenario 1 has four cases (U1-U4), where the urbanization with the change in urban coverage of land cover map varies from 10% to 70% (Table 3). Using NLCD land cover for the years 1992, 2001, 2006, 2011, and 2050 (scenario 2), cases LU1 to LU5 were created to evaluate the actual change in the past. The effectiveness of LID practices for reducing runoff was evaluated using scenario 3 for the land-use 2011 (cases L1-L3). Furthermore, cases C1 to C5 of scenario 4 were used to study the climate change impacts from different rainfall projections without the incorporation of LID structures in the model. For all scenarios, we assume that the contribution of inflow station US02168504 is stationary.

3. Results

3.1. PCSWMM: Model calibration and validation

The sensitivity analysis was conducted using the SRTC tool. It was observed that the sub-catchment width, slope, percent of imperviousness, and curve number were the most sensitive parameters. Our result is consistent with the findings from Ahiablame and Shakya (2016), Akhter and Hewa (2016), Abdul-Aziz, and Al-Amin (2016). The goodness of fit index Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970) and coefficient of determination (R^2) were used to evaluate the performance of the PCSWMM hydrologic model using daily streamflow at the downstream station US02169500. The coefficient of determination R^2 is defined as the squared value of the correlation coefficient. The NSE is considered to be the most appropriate relative error or goodness-of-fit measure available owing to its straightforward physical interpretation (Legates and McCabe, 1999). The NSE and R^2 values for calibration period (2006-2015) are 0.79 and 0.81, and for validation period (2000-2005) are 0.76 and 0.80 respectively (Figure 3a). The goodness of fit measures NSE and R^2 values of the range 0.8 are considered a good fit indicator for model performance on a daily scale (Vu et al., 2017b).

We compared the additional goodness of fit indices such as NSE for $Q^{0.2}$ and RMSE for the logarithm of streamflow (Nicolle et al., 2014, Vu et al., 2017b) between the simulated and observed runoff. The NSE results for $Q^{0.2}$ for calibration and validation are 0.96 and 0.94, while the RMSE on ln(Q) are 0.52 and 0.53, respectively. This additional goodness of fits on low flow suggests the study region's PCSWMM model's better performance during the dry season. The calibrated PCSWMM model still underestimated the high flow for a specific year in 2012 and 2014 (Figure 3a). The model also underestimated the peak flow for 2001, 2002, and 2004. Erickson et al. (2010) explained this underestimation of runoff volume in the SWMM model could be associated with the "off the top" approach, which suggests that evaporation is subtracted during a rainfall event before infiltration and runoff are estimated (James et al., 2008). This may lead to the underestimation of runoff (Schomberg et al., 2000). Similar findings are observed in previous studies by Pinos and Timbe (2019), Broekhuizen et al. (2020), and Larabi et al. (2018). In this study, the calibrated PCSWMM model matched well with the historical flooding event in 2015 (Figure 3b). Both NSE and R^2 for the simulation of the thousand-year return period flooding event in 2015 are above 0.98 compared to observed data. This is similar to other event-based simulations as in Borah et al. (2007), Mejia and Moglen (2010), Hossain et al. (2019).

3.2. Impact of Urbanization and land-use change on runoff

Two land-use scenarios are evaluated in this study. In the first scenario, four cases (U1 to U4) are investigated by increasing the urbanization area between 10% to 70% concerning the baseline land cover (NLCD 2011). In the second scenario, four actual land-use cases (LU1 to LU4) based on the NLCD for the years 1992, 2001, 2006, and 2011 are considered, and in addition to that, the projected land-use (LU5) for the year 2050 is also included (Table 3).

The calibrated model PCSWMM was simulated for the whole study period of 2000-2015 using four different land cover cases (Scenario 1, Table 3) by increasing urbanization from the baseline period (NLCD 2011). Due to the transition from the pervious to the impervious surface, the infiltration and groundwater flow is reduced; hence, more runoff is expected to occur. Compared to baseline (using NLCD 2011), all urbanization cases show an increasing trend in the mean annual runoff. The mean annual runoff simulated based on the four (U1-U4) cases (Figure 4) indicated a steady increase when increasing the impervious area. The increase in impervious cover has a significant impact on the extreme event; in particular, the peak flow during the 2015 historical flood indicates that by increasing (with a based period 2011) the impervious surface to

10%, 30%, 50%, and 70%, the corresponding annual flow likely to increase by 25%, 45%, 80%, and 120%, respectively.

Different land-use maps (LU1-LU5) obtained from NLCD for four different years 1992, 2001, 2006, 2011, and the projected map for 2050 was used as input to the calibrated PCSWMM model to simulate flow during the study period 2000-2015. The average annual runoff computed for LU1 to LU5 based on the percentage of urban areas for each NLCD year. The percentage of urban areas for the year 2050 was extrapolated using the exponential fitting curve based on the four NLCD survey years (Table 1). As the percentage of the urban area (%) increases, the simulated mean annual runoff volume also increases to the magnitude of 108, 120, 128, 135, and 167 thousand m^3/day corresponding to the year 1992, 2001, 2006, 2011, 2050 respectively (Figure 5). In comparison with the land-use map in 1992, the projected land-use in 2050 has increased mean annual runoff volume of 54%. In a nutshell, urbanization leads to an increase in the impervious area, reducing groundwater flow and increasing surface runoff.

3.3. Impact of LID on runoff

Two commonly used LID practices (rain gardens and rain barrels) are evaluated to minimize excessive runoff under extreme weather conditions. The rain barrel (case L1) collects water from shingle roofs into buckets, whereas the rain garden (case L2) temporarily stores excessive water in the underground storage. The combination of both rain garden and rain barrel (case L3) is investigated, although this seems to be a more expensive selection. The calibrated PCSWMM model was used to investigate the three LID cases (L1, L2, and L3) based on the NLCD 2011 for the study period 2000-2015 (Figure 6) in comparison with the scenario with no LID application. In this study, the simulation was based on daily runoff, showing the effect of LID controls only on the volumes of the flood events but not on the peak flows. Overall, by incorporating the LID practices, the mean annual runoff volume was reduced for all simulated years; however, the performance of LIDs varies widely. Compared to without LIDs, the rain barrel approach (L1) reduced the total annual runoff by about 10%. The rain garden approach (L2) can further capture the roof's rainfall amount to its underground storage and reduce the total annual runoff to 21%. The combined system (case L3) can hold up the excess runoff to its maximum capacity of 32%. In any LID scenario, it is observed that during small rainfall conditions, the runoff can sufficiently be stored in its storage layer, generating a lesser amount of runoff. However, during increased rainfall conditions, the LID elements' storage capacity is insufficient, thus causing the increased runoff values. Although this runoff is still lesser than the runoff observed in the baseline scenario, the percentage of runoff volume reduction is not significant due to the LID elements' size limitation.

3.4. Impact of climate change on runoff

The previous sections discussed the relationship between urbanization, land cover changes, stormwater control using LID practices, and surface runoff. This section analyzes the potential influence of climate change scenarios and land cover projection on urban runoff compared to the baseline climate. In scenario 4, five cases (C1-C5) are evaluated based on the GCMs rainfall downscaled from the five selected NARCCAP models as tabulated in Table 2. The baseline climate data is bias-corrected with observed data using the non-parametric quantile mapping approach. The projected climate data is bias-corrected using the equidistance quantile mapping approach. The bias-corrected precipitation is then used as input to the calibrated PCSWMM model for (1) baseline climate 1968-1999 using the land cover map from NLCD 1992 and (2) projected climate 2038-2069 using the land cover map from NLCD 2050. The daily runoff output from the PCSWMM model is used for further evaluation.

In this study, the mean annual runoff volume computed for the baseline and projected scenarios are evaluated (Figure 7). The result displayed in Figure 7 clearly shows the uncertainty among NARRCAP models. For instance, using the same GCM CGCM3, the RCM3 indicated a slightly higher mean annual runoff captured at the Columbia station than CRCM. The anomaly in the projected runoff for CGCM3-RCM3 with respect to baseline is about 65% compared to 55% for CGCM3-CRCM. Figure 7 also exhibits the climate sensitivity among different GCMs. For example, the Canadian GCM CGCM3 produces more rainfall than the American GCM CCSM, which was downscaled using the same CRCM. The GFDL is wetter than CGCM3 (downscaled by the same RCM3). However, the climate sensitivity uncertainty is different in the anomaly calculation. The anomaly is significantly higher in CGCM3-RCM3 (65%) compared to GFDL-RCM3 (40%), but it is the same for other CCSM-CRCM and CGCM3-CRCM (both at 55%). Overall, there has been a significant increase in runoff volume based on the projected climate and land-use scenarios compared to the baseline runoff. The percentage change ranges from 40-70% in mean annual runoff at the selected stream gauge station. It is noted that the projected land-use in 2050 can potentially increase the mean annual runoff volume of up to 54% compared to the land-use map in 1992.

4. Conclusions

This study utilizes the urban hydrologic model PCSWMM in simulating the surface runoff for the Upper Congaree River and Outlet Saluda River near Columbia, South Carolina. The city witnessed a thousand-year event rainfall in October 2015, resulting in a 2 billion dollars loss of damages. Due to the rapid urbanization and the reduced hydrologic time of concentration, the time to peak and the magnitude of surface runoff increased, leading to difficulty in draining the massive stormwater in a short amount of time. The PCSWMM is used to perform the potential influence of climate change, land uses, and LID practices on urban flooding. Various scenarios are evaluated to demonstrate the ability of LIDs to mitigate urban runoff due to the rapid increase in urbanization and climate change. The following observations were made in this study:

(a) Urbanization leads to an increasing impervious surface, which resulted in reduced infiltration and groundwater flow and higher surface runoff. Mainly, during a thousand-year return period storm event (e.g., occurred in 1st week of October 2015), the existing infrastructure could not withstand the most severe flooding. If the impervious cover increased by 10%, 30%, 50%, and 70%, the annual flow might increase by approximately 25%, 45%, 80%, and 120%, respectively, compared to the baseline land cover NLCD 2011.

(b) Flood mitigation level using Low Impact Development practices is evaluated based on three different approaches: rain barrel, rain garden, and a combination of both. For this particular catchment area, LID plays a significant role in mitigating the water runoff with an average reduction of 10%, 21%, and 32%, respectively, for the three approaches. Rain gardens proved to be more effective than rain barrels to reduce runoff, while the combination of both LIDs performed best. The cost-effectiveness of the LID practices plays a pivotal role when choosing LID practices.

(c) In comparison with baseline climate (using baseline land cover), it is expected that the percentages of mean annual runoff volume will increase by 40-70% based on the projected land-use (2050) and climate change scenarios (2038-2069).

In addition to installing LID components, the improvement of existing storm drainage infrastructures also needs to be prioritized. When integrated with improved traditional drainage forms, LIDs can successfully manage stormwater runoff under the future urbanization and climate change scenario. This study can be further extended to evaluate other LID controls like porous pavements, vegetative swales, etc. The potential future work can focus on developing a robust downscaling procedure for urban hydrology-related applications by adequately addressing uncertainties associated with global climate models and sparse data and capturing the extreme rainfall events and sub-daily rainfall for urban flooding applications. This extreme rainfall information can help to improve instantaneous peak flow from daily flow data to assess the LID effects not only on runoff volumes but also on instantaneous peak flow.

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Conflict of interest:

We have no conflict of interest to report.

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Table 1. Land use classification for the selected watershed

Landuse type	Percentage of watershed area (%)			
	Year 1992	Year 2001	Year 2006	Year 2011
Urban area	60.21	65.45	67.69	68.44
Non-urban area	36.2	29.7	27.54	26.81
Water/Wetland	3.59	4.85	4.77	4.75

Table 2. NARCCAP models used for study

Global Climate Models (GCM)	Regional Climate Models (RCM)	Selected GCM-RCM combination
CCSM (NCAR Community Climate System Model)	CRCM (Canadian Regional Climate Model)	CCSM-CRCM
CGCM3 (Canadian Global Climate Model v.3)		CGCM3-CRCM
	RCM3 (Regional Climate Model v.3)	CGCM3-RCM3
		GFDL-RCM3

GFDL (Geophysical Fluid Dynamics Laboratory)	ECP2 (Experimental Climate Prediction Center)	GFDL-ECP2

Table 3. Different scenarios used in this study

Scenario	Case	Description	Land use	Precipitation	Period
1	U1	10% urbanization	NLCD2011	Observed from NOAA	2000 to 2015
	U2	30% urbanization			
	U3	50% urbanization			
	U4	70% urbanization			
2	LU1	1992 land use	NLCD1992		
	LU2	2001 land use	NLCD2001		
	LU3	2006 land use	NLCD2006		
	LU4	2011 land use	NLCD2011		
	LU5	2050 land use	Predicted 2050		
3	L1	Rain barrel only	NLCD2011		
	L2	Rain garden only			
	L3	Both LID			
4	C1	CCSM-CRCM	NLCD1992 for baseline; Predicted 2050 for future	From model	Baseline 1968 to 1999 Projection 2038 to 2069
	C2	CGCM3-CRCM			
	C3	CGCM3-RCM3			
	C4	GFDL-RCM3			
	C5	GFDL-ECP2			

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