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**Assessing the effects of climate change on urban watersheds: a review and call for
future research**

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Draft

Abstract

Considerable efforts have been made to control and manage hydrology and water quality of watersheds impacted by urban development through construction of stormwater control measures (SCMs). Climate change (CC) could, however, undermine these efforts through intensifying precipitation and hydrologic extremes. Although the impact of CC on water resources has been well-documented, its impact on urban hydrology remains less studied. CC may complicate sustainable urban hydrology, which can cause reduction in SCM efficiency with changes in precipitation pattern (i.e., change in duration, frequency, depth, and intensity). More intense precipitation may result in reduced runoff reduction and treatment efficiency given that SCMs have the finite surface storage volume and surface infiltration capacity. Determining the functionality of various SCMs under future climate projections is important to better understand the impact of CC on urban stormwater and how well these practices can build resiliency into our urban environment. The purpose of this review is to provide the needs and opportunities for future research on quantifying the effect of CC on urban SCMs and characterizing the performance and effectiveness of these systems under existing and projected climate scenarios. A summary of the modeled constituents as well as the stormwater and climate models applied in these studies is provided. We concluded that there are still limitations in exploring the impact of future change in meteorological variables will influence the operation of SCMs in the long-term. Previous studies mostly focused on the impacts of CC on urban runoff quantity and only handful studies have explored water quality impacts from CC such as potential changes in water temperature, metals and pathogens. Assessing pollutant removal efficiency of SCMs such as bioretention, infiltration trenches, dry and wet swales, rooftop disconnections, wet and dry ponds, which are common practices in urban watersheds, also needs more attention. Analysis on

the cost of adapting SCMs to CC to maintain the same performance as current climate conditions is also recommended for future research.

Keywords: urban runoff quantity and quality, stormwater control measures, climate change, resiliency, watershed restoration.

1.0 Introduction

Evaluating the impacts of climate change (CC) on urban watersheds is a critical need in water resource management (Velpuri and Senay, 2013). Over the coming decades, global population is expected to grow with much of that increase taking place in cities, increasing urbanization worldwide (Galea et al., 2019). Population growth and urbanization increase imperviousness, resulting in urban flooding (Pyke et al., 2011; Walsh et al., 2012; Elga et al., 2015) and pollutant washoff to streams, lakes and rivers (Hatt et al., 2004). Urbanization also increases nutrient (Foley et al., 2005; O'Driscoll et al., 2010; Lin et al., 2020), and as nutrients increase in water bodies, eutrophication ensues (USEPA, 2010; Bell et al., 2017; Rodríguez-Gallego et al., 2017; Minaudo et al., 2019). CC may increase these impacts even further (Najjar et al., 2010; Hathaway et al., 2014) as this potentially constrains policymakers' ability to achieve future water quality goals. CC also reduces the functionality of stormwater control measures (SCMs), which are the mitigation practices used in urban areas to reduce pollutant loads, decrease peak storm flows and provide additional benefits such as water supply, recreation, habitat and biodiversity to achieve restoration goals. SCMs are designed based on the stationarity, which is the main limitation in the current design practice of these measures. This stationary assumption has been shown to be no longer acceptable (Milly et al., 2015) and needs to be updated in the design of urban stormwater systems.

Management of urban stormwater systems under CC is a critical step to better predict runoff quality and quantity under uncertain climate condition and provide process-based information about new adaptation strategies for protecting water quality and ecosystem functionality. This paper undertakes a review of the impacts of CC on urban stormwater, including runoff impacts and potential mitigation methods, CC scenario selection, downscaling approaches, and CC studies in urbanized watersheds. We summarize the constituents of concern (e.g., streamflow and pollutants) as well as the stormwater and climate models applied in these studies. Limitations of the current body of literature are identified. The needs and opportunities for determining the impacts of CC on water quantity and quality in urban areas are also discussed to help guide future research.

2.0 Approach

This paper reviews the literature from peer-reviewed journals, conference proceedings, book chapters, design guidelines, technical manuals, case studies and technical reports, and project reports. We search a number of key words, including best management practices (BMPs), green infrastructure (GI), urban runoff, water quality, climate change (CC), changing climate and climate variation.

More than 100 publications were searched primary from publications in ISI Web of Knowledge, the Colorado School of Mines Library database, Wiley, International Journals, PubMed, Google Scholar, Open Access Journals, among others. The selected publications were categorized by climate change, urbanization, urban stormwater management, and green infrastructure to facilitate presentation of the information. Through the search process, articles published through June 2020 were selected for final review.

Multiple inclusion and exclusion criteria are considered in this review based on 145 papers. We identified the most relevant articles based on the selected criteria. Studies related to SCM performance (runoff reduction, and water quality improvement), the impact of climate change on the SCM performance, urbanization and urban stormwater, were included. Studies about the management strategies that are not related to SCM were excluded. Performance criteria such as thermal effects of SCMs, air quality improvement and environmental risk assessment were also excluded.

3.0 Urban Systems and Climate Change: A Brief Review of Key Concepts

This initial section provides a brief review on urbanization, SCMs, and climate models and scenarios. Given that the ultimate goal of this paper is on a review of the longer-term impacts of CC on urban stormwater, we only summarize major points on these topics, with the goal of providing the reader with general an overview of the current literature.

3.1 Urbanization Impacts on Watersheds

Remediating the degradation of surface waters as a result of urban development is a major focus of water resources planning worldwide. Urbanization increases imperviousness, resulting in urban flooding (Elga et al., 2015) and pollutant washoff to streams, lakes and rivers (Liu et al., 2018; Fu et al., 2021)). Urbanization also increases nutrient export (Foley et al., 2005; Gold et al., 2019), and as nutrients increase in water bodies, eutrophication ensues. Nitrogen, phosphorus, sediment, metal, bacteria, and other contaminants are controlled by the combination of biological, chemical and physical process driven by hydrologic transport (Hirsch, 2012; Khatri et al., 2015).

Urban development will also result in erosion and channel scour (Kaushal and Belt, 2012; Nelson and Booth, 2002; Taniguchi et al., 2018; Nayeb Yazdi et al., 2019). Hatt et al., (2004)

found that in a small urban catchment, total phosphorus was strongly correlated with the percent of imperviousness and degree to which it is hydraulically connected with receiving streams. Nelson and Booth (2002) studied the effects of land use change on annual sediment yields and found that channel and road-surface erosion were the important factors affecting sediment yields by 50%. Alberti et al., (2007) and Schueler et al., (2009) found that urbanization likely results in significant degradation of the biotic integrity of streams. Elevated nutrient levels in urban areas contribute to aquatic “dead zones” affecting many streams, rivers, lakes and estuaries worldwide (Joyce, 2000; Altieri et al., 2019). To restore impaired waters, the U.S. Clean Water Act established total maximum daily loads (TMDLs), restricting pollutant loads in discharges to rivers, streams, and lakes. Reductions in most pollutant loadings can generally be achieved by implementing watershed management practices such as SCMs.

3.2 Stormwater Control Measures

SCMs include infrastructure on a grey to green continuum (Bell et al., 2019) Common “greener” SCMs include green roofs, bioretention systems, porous pavement, wet ponds, extended detention ponds, grass swales, and infiltration trenches, that help to decrease runoff volume and peak and pollutant loadings (Baden Myers BE and van Leeuwen MEnvSc, 2011; Hunt et al., 2006; Bedan and Clausen, 2009; Davis et al., 2009; Hathaway et al., 2008; Avellaneda et al., 2017; Epps and Hathaway, 2019; Jefferson et al., 2017; Kuehler et al., 2017; Liu et al., 2017; Ahmadisharaf et al., 2016; Alamdari, 2016; Alamdari et al., 2021). Historically, SCMs have been used to simply attenuate peak flows; however, SCM function has expanded to include water quality treatment of runoff. The objective of SCMs is to restore the hydrology of an urban site to pre-developed or more natural conditions (Prince George’s County, 1999) and to reduce runoff and increase infiltration, groundwater recharge, stream protection and pollutant

removal. SCMs also improve the infiltration and storage capacity of an urban catchment (Askarizadeh et al., 2015). These practices also remove pollutants through chemical, physical and biological processes. The benefits of SCMs in watershed restoration and management are well documented in previous review papers (Ahiablame et al., 2012; Laforteza et al., 2013; Liu et al., 2016; Wolfand et al., 2018; Read et al., 2019; Gallo et al., 2020). However, most of past studies have focused on historical climate conditions without considering future changes in climate patterns.

3.3 Climate Change Predictions

CC could alter precipitation and runoff, thereby intensifying the risk of hydrologic extreme events. Future climate emission scenarios have been developed based on expected changes in the global economy, environment and population (Pachauri et al., 2014; Muratori et al., 2017). CC may lead to increase in average temperature from 1.1 to 6.4 °C by 2100 across the world (Field, 2014).

Hayhoe et al. (2008) evaluated the precipitation change in northeastern U.S. and found precipitation increases by 2100 for different climate emission scenarios (A1F1 and B1) especially during winter and spring for northeastern U.S. Mote and Salathé (2010) predicted large precipitation changes by 2100 for different climate emission scenarios (A1B and B1) especially during fall and summer in the Pacific Northwest of the U.S. The impacts of CC on climate variables were investigated by Feng et al., (2019) in 135 coastal watersheds in California. They found large changes in intensity and frequency storms specially those larger than 36 mm/day, whereas moderate changes ($\pm 3\%$) in annual precipitation. While there are numerous studies of assessing trends in precipitation extremes, they have not been applied to evaluating the resilience of stormwater systems, which typically requires event-based inputs,

involving selection of a design storm, or continuous inputs for longer-term assessment (Rangarajan et al., 2012).

4.0 Climate Change Impacts on Urban Centers

CC will aggravate the negative effects of urbanization by changing temperature and precipitation patterns. Temperature change for all the U.S. cities were investigated in the study by Mishra and Lettenmaier, (2011) from 1950-2009. They found significant increases in temperature for almost all cities across the U.S. and extreme precipitation for almost 30% of them. Milly et al., (2015) and Yang and Zurbenko (2010) suggest that the demise of stationarity provides an opportunity to incorporate uncertainty analyses from all sources into water management analyses. These changes due to CC suggest the need to consider CC impacts into design of urban stormwater systems and drainage infrastructure. Overall, 20 studies explored the effects of CC on urban runoff quantity and quality. Table 1 summarizes past studies on the CC impacts on stormwater runoff.

Table 1. Summary of studies performed for assessment of runoff quantity and quality under climate change

Climate data in these studies are predicted either using climate models such as a GCM or a coupled GCM-RCM. Future emission scenarios are employed to make predictions of future CC; these include the 2000 Special Report on Emission Scenarios (SRES) (Nakićenović and Swart, 2000) and the 2010 Representative Concentration Pathways (RCP) (Moss et al., 2010). The predicted climate data would be input hydrologic models to simulate the runoff quantity or quality. Based on the findings of several studies on CC impacts, these studies observed the negative impacts of CC on runoff volume and peak, sediment, nutrients, bacteria and etc.

Semadeni-Davies et al., (2008) evaluated the effects of CC and land use change on flow volume and peak in south Sweden using medium and high climate emission scenarios along with two land use change scenarios. Authors found that watershed hydrology was affected more by CC compared to urbanization. Franczyk and Chang (2009) used a combination of CC and land use/ land cover (LULC) change to investigate the changes in runoff depths in the Portland, Oregon metropolitan area and found a moderate increase in annual runoff. Li et al., 2020 developed a framework to quantify the effects of climate variability and LULC change on runoff. The results indicated decreased precipitation and runoff during the period 1951–2013 and climate variability had more pronounced effects on runoff than LULC change. Giri et al., 2019 developed an integrated modeling framework to simulate LULC change in the Neshanic River Watershed. They also evaluated various hydrological processes under CC and LULC change scenarios. Results indicated that the changing climate will have a larger effect on the hydrological processes than urbanization in the study watershed. These analyses suggested that both CC and LULC change should be incorporated in hydrological models to better understand the effects of these two nonstationary factors on hydrological processes.

Conversely, there have been handful studies focused on CC impacts of water quality especially in the U.S. Pollutants such as sediment and nutrients have received more attention in CC studies; other contaminant such as water temperature, heavy metals, pathogens, toxics, and etc. have been mostly overlooked. Alamdari et al., (2017) investigated the impacts of CC on runoff quantity and quality in a highly urbanized watershed in Virginia. CC simulations showed that annual runoff, TSS, TN and TP would increase, with even larger seasonal variability. There is a paucity of studies focusing on CC impacts on pollutant loads such as *E. coli*, zinc, copper and lead in the U.S.

Most studies have also focused on runoff depth, volume, and peak flow, with little attention to other runoff attributes such as time to peak, hydrograph duration, and rising/falling limbs which are important characteristics of a storm hydrograph (Foufoula-Georgiou et al., 2015). Additionally, most of the studies have been undertaken in the eastern U.S., while the western U.S. has not received as much attention, most likely because flood extremes are more pronounced in wetter climates of the eastern U.S. While CC impacts on surface runoff quantity in the western U.S. might be less important, impacts on groundwater recharge and drought could be significant. These past studies have highlighted the need for further analysis of CC impacts on stormwater runoff conditions, especially in the western U.S., to better guide climate adaptation strategies in urban communities, thereby more reliably improving watershed health.

5.0 Hydrological issues associate with climate change and urban development

Evaluating the impact of greenhouse gas production on climate variation has been the subject of much interest, particularly in vulnerable urban communities. CC can alter the magnitude of precipitation, the spatial and temporal distribution of rainfall, as well as the frequency of extreme events. CC can also increase the duration between events which can lead to drying out of soil moisture levels and reduced groundwater recharge and baseflow in streams, decreasing streamflow during dry weather (Jacobson, 2011; Fletcher et al., 2013; van Dijk et al., 2013; Saft et al., 2015). Land cover in growing urban areas is also transforming due to socioeconomic and biophysical factors (Lambin et al., 2001) resulting in significant changes in runoff and water quality (Hovenga et al., 2016). LULC change negatively affects the hydrological processes in a watershed, leading to a degradation of water quality. For example, urbanization leads to increases in the proportion of impervious surfaces in watersheds, which in turn results in increased runoff and pollutant loads (Elga et al., 2015), increasing pollutant

washoff to rivers, streams, and lakes (Hatt et al., 2004). Climate change may increase the impacts of LULC change even further (Hathaway et al., 2014; Lee and Jetz, 2008; Semadeni-Davies et al., 2008) as runoff is directly related to precipitation, thus, increases in precipitation will directly lead to increases in runoff, potentially increasing pollutant washoff to downstream water bodies. For example, Guo et al., 2020 developed an integrated modeling framework to assess the effects of individual and combined CC and LULC on the streamflow of Xinanjiang Basin, China. Results indicated that both LULC and CC individually and combined, projected an increase in streamflow. They also found that the changes in annual streamflow are mainly due to changes in LULC. Luo et al., 2020 assessed the individual and combined effects of future CC and LULC on the flow and nutrient load in the Xitiaoxi watershed, China. The results of combined CC and LULC change indicated that flow and nutrient load would be more affected by CC than LULC. Hovenga et al., 2016 evaluated the response of runoff and sediment loading in the Apalachicola River under projected CC and LULC change. Results indicated that CC may lead to seasonal shifts for both runoff and sediment loading. Changes in LULC showed increased in sediment loading was due to increased agriculture and urban areas and decreased forested areas. Farinosi et al., 2019 analyzed the hydrological alterations caused by CC and LULC changes. The analysis indicated that CC and LULC change are expected increase in interannual and intraannual variability.

The extent to which sediment and nutrient loads will be impacted by those changes is of interest for effective design of SCMs. Improvements in the understanding of how climate and LULC changes impact water quality and quantity in urban watersheds can assist in selecting the best implementation strategies. Land use or town planning would ameliorate hydrological issues associated with CC and urban development. For example, Suriya et al., 2011, evaluated the

effects of urbanization on flooding in Thirusoolam sub watershed, an urban watershed in Chennai and developed an integrated approach for flood management and flood risk reduction, considering the LULC change into the hydrological model and accurate prediction of the surface runoff changes. Patel et al., 2013 integrated the high-resolution remote sensing images and GIS datasets to prepare the flood zone mapping of Surat district, Gujarat, India. Authors found that more than 90–95 % of the area would be flooded in the near future and various mitigation strategies such as water storage structure in form of reservoir, polder and cutoff are suggested to reduce the danger of flooding in the future. Chen et al., 2015 developed a spatial multi-criteria decision-making tool for the evaluation of flooding risk in Queensland, Australia. They identified and evaluated flood risk while employing adaptation strategies and found significant flood reduction under future CC. Liu et al., 2016 applied green infrastructure to reduce the negative effects of CC and LULC change in Trail Creek Watershed, Indiana. They found the reduction of 9.0%-14.4% for runoff volume and pollutant loads using detention basin and grass swales. These results of these studies suggest a complexity of the impacts of LULC change and CC on hydrological processes, and have implications for urban planning, and decision making related to urban stormwater runoff quantity and quality.

6.0 Climate Change and Resiliency of Stormwater Systems

SCMs can be used as climate adaptation strategies to mitigate potential CC impacts in the future (Gill et al., 2007; Pyke et al., 2011, Hadi Pour et al., 2020; Silva et al., 2018). Hadi pour et al., 2020 analyzed the effectiveness of SCMs in the mitigation of urban flooding. The results indicated that SCMs are efficient methods for ameliorating urban flooding. Silva et al., 2018 assessed the effects of stormwater management to mitigate flooding in an urban watershed located in São Paulo, Brazil. Results show that the drainage system modification can help reduce

flood damage in the future. However, the CC needs immediate attention and action from urban planners, decision makers, and stakeholders. Although installation of a SCM has generally positive effects in urban centers and can mitigate the adverse impacts of CC and urbanization, some recent studies focused on the resiliency and functionality of these systems under uncertain projected future climate. CC may aggravate the impacts of urbanization by increasing urban runoff hydrograph attributes—volume, timing and peak—and overwhelming stormwater systems (Semadeni-Davies et al., 2008). Kirshen et al., (2014) assessed the impacts of CC for 10- and 100-year storms for 2070 and found that LIDs alone could not withstand the negative impacts of CC. Twenty-three studies have recently examined how the efficiency of SCMs might be affected due to CC, these are summarized in Table 2.

Table 2. Summary of studies performed for assessment of SCMs under climate change.

A variety of SCMs, including bioretention, retention ponds, green roofs, and rainwater harvesting systems were evaluated in these studies. CC studies mostly focused on the ranges between year 2020 and 2100 for the predictions. Rainfall data were predicted using GCM or RCM and emission scenarios such as SRES and RCP. The predicted climate data then forced watershed models to simulate the efficiency of SCMs.

Many studies found the negative impacts of CC on SCMs with increasing frequency and magnitude of rainfall compared to base observed scenario. For example, Hathaway et al., (2014) evaluated bioretention functionality under CC scenarios for several locations in North Carolina, U.S. and found that frequency and magnitude of flows would likely increase in the face of CC scenarios. Sharma et al., (2016) investigated the impacts of CC on the removal efficiency of retention ponds in Denmark, and found that increase in rainfall intensity and duration will influence the functionality of retention ponds by increasing more pollutants entering to these

systems and decreasing hydraulic retention time of the pond during such extreme events (Sharma et al., 2016). Such impacts should be considered in order to have resilient SCMs for projected CC conditions.

Rainwater harvesting (RWH) systems are effective strategies to mitigate the effects of CC as shown by several studies (Aladenola and Adeboye, 2010; Kahinda et al., 2010; Boelee et al., 2013). The reliability and resiliency of RWHs is important for urban communities to achieve water supply goals and needs in the face of uncertain CC conditions. Alamdari et al., (2018a) investigated the impacts of CC on water supply and runoff capture reliability of RWHs in 17 metropolitan areas across the U.S. and found likely decrease in the resiliency of RWH systems.

Recently, several studies have explored future CC on SCM resiliency and reliability. Recent advancement in downscaling and bias correction of GCMs makes it feasible to couple these climate models with continuous watershed models to estimate the plausible effects of CC on hydrology and water quality. Yet, uncertainty remains, due to uncertainty of the climate models, algorithms, configuration, equations and assumptions. Sheffield et al., (2013) compared different climate models and found that they differently predict climate variables, including extreme precipitation, precipitation intensity, annual temperature, and inter-annual and decadal variability.

These reviewed studies accentuate more research on comprehensive analysis of CC conditions to enhance the reliability, functionality and resiliency of SCMs in the future. Such studies would help planners and decision makers to better implement sustainable and restorative development projects by designing and managing SCMs to achieve broader environmental, economic and social goals throughout the complete lifespan of a project and considering future CC.

7.0 Future Research Direction

Changes in rainfall magnitude and intensity from CC may cause urban infrastructure to fail, as documented by past studies (Abrishamchi et al., 2011; Ahmadisharaf & Kalyanapu, 2015; Alamdari et al., 2018a; Alamdari et al., 2018b; Giese et al., 2019; Alamdari et al., 2020; Giuffria et al., 2017). Most of these focus on runoff quantity and only a few studies have focused on evaluating the performance of SCMs subject to CC. There is a need to evaluate the treatment efficiency of SCMs in the future. The ability to assess the impact of CC on both hydrologic and water quality treatment could assist in the selection of the most appropriate SCMs to address water management goals and conserve limited financial resources under CC.

Several studies focused on the efficiency of bioretention, porous pavement and rainwater harvesting systems. However, there is a lack of progress on assessing the efficiency of other SCMs such as infiltration trenches, dry and wet swales, rooftop disconnections and extended detention basins in response to CC. Improving our understanding of how CC impacts the pollutant removal efficiency of SCMs would help water resources managers to implement adaptation strategies to future changes due to CC and urbanization.

Our review also showed that most studies investigated the impact of CC on runoff volume and peak flow, with little attention to other attributes such as hydrograph duration and the rising or falling limbs, or time to peak. Studying runoff volume and peak only provides limited information about flood dynamic in a watershed. Future research on these other attributes provides insights on hydrologic response of a watershed such as hydrograph flashiness (Ahmadisharaf et al., 2018; Foufoula-Georgiou et al., 2015).

Additionally, most of the available studies were undertaken for sites in the eastern U.S., while the western U.S. has not received as much attention. While CC impacts on surface runoff

quantity in the western U.S. might be relatively low, impacts on groundwater recharge and drought, as well as water quality, could be significant. We note that studying CC impacts on the western U.S. is an important area for future research.

Pollutants such as sediment and nutrients have received more attention in CC studies; other contaminant such as water temperature, heavy metals, toxics and pathogen have been mostly overlooked and should be investigated to help achieve watershed broader restoration goals.

Most of the studies assessed the effects of CC on the sediment and nutrient removal efficiency of SCMs, however no studies to date evaluated the effects of CC on the infiltration and groundwater recharge potential of SCMs. SCMs have the potential to promote groundwater recharge and increase water supply availability especially in arid and semi-arid regions (Newcomer et al., 2014; Moores et al., 2018). We suggest that studying CC impacts on the arid and semi-arid regions is an important area for future research.

Watershed models are used to explore the impact of CC on urban systems (Read et al., 2019; Gallo et al., 2020; Alamdari et al., 2020). The accuracy of these models is tightly linked with the accuracy of future projections and subsequently the reliability and risk of investment in protection or mitigation measures. Assumptions in the hydrologic models, inaccurate field data and associated uncertainty with physical processes such as buildup and washoff affect the accuracy of simulated runoff quantity and quality. Future work should include uncertainty analysis on parameters and variables in the hydrologic model, to communicate the plausible risks with managers and support more informed decisions. Most of the watershed models applicable to urban areas are not capable of simulating SCMs. This limitation could be one reason that studies on the impacts of CC often do not extend to efficiency of the SCMs.

There is also an uncertainty associated with the assumptions in climate models and scenarios. Addressing this limitation through incorporating a full analysis of uncertainty are recommended to more reliably project the impacts of CC. Stochastic models should be applied to project future conditions by incorporating uncertainties. However, extensive computational time might hinder their applications, particularly for continuous modeling that is required for CC impact studies. Enhancing computational efficiency of existing watershed models through application of parallel processing and graphics processing units should be also another area in future research.

In the age of CC, one important question is the potential impact of long-term CC or greater climate extremes and how they alter hydrologic and biogeochemical processes. Development of effective land management strategies to improve water quality will require a fundamental understanding of how landscape units interact. Developing predictive frameworks that explain interactions among climate, hydrology, biogeochemistry and economy will inform new and more effective watershed protection strategies.

LULC change coupled with CC may accelerate pollutant transport from the watershed to sensitive receiving water bodies. The findings of this review are facilitating the understanding of the scale of the potential effects of changes in LULC and climate on water quantity and quality from the watershed. Our analysis suggests that runoff, sediment and nutrient loads will likely change in the future, so, further studies related to watershed mitigation strategies such as implementation of SCMs should be conducted to minimize the adverse effects of climate and LULC changes to ensure future water quality goals are met.

SCM planning needs to be revisited in urban watersheds under CC. We need to identify the most optimized combination of SCMs at the minimum cost to achieve the restoration goals in

the face of CC. There are many limitations, including site constraints, and climate conditions which should be considered in order to select the most appropriate combinations. Developing simulation-optimization and decision support system tools will assist in the evaluation of watershed protection strategies and development and implementation of TMDLs to achieve watershed restoration goals.

The efficiency of SCMs for existing and projected climate scenarios can be evaluated to identify how these measures can be adapted to keep the same level of performance with CC. In a sustainable point of view, those strategies that are most resilient to CC, also provide additional flood/drought risk reduction benefits and assist in water supply and quality management. Completion of such studies can assist water resources managers, local governments, decision makers, and watershed groups to better manage water quality and quantity in urban communities.

8.0 Conclusion

The current paper reviewed existing literature on the impacts of CC on stormwater quantity and quality and on the performance of the SCMs. We concluded that there are still limitations in determining how future change in precipitation intensity, duration, frequency and temperature will influence the operation of SCMs in the long-term. Most previous studies focused on the effects of CC on urban runoff quantity and only handful studies have explored the impact of CC on water quality such as potential changes in water temperature, metals and pathogens. Assessing the pollutant removal efficiency of SCMs such as infiltration trench, dry and wet swale, rooftop disconnection and extended detention basin, which are common practices in urban watersheds, needs more attention. Analysis on cost of adapting SCMs to CC to maintain the same performance as the current climate conditions is also recommended for future research.

More in-depth research is also needed to represent regional variability and scientific uncertainty. Design and optimization of SCMs that consider CC impacts and co-optimize this with other goals and objectives such as habitat protection and ecosystem services will become increasingly important in the future. CC likely brings additional uncertainty into the existing uncertainties in watershed models and will make reliable prediction of hydrologic extremes (floods and droughts), and the fate and transport of pollutants, even more difficult.

Accounting for the nonstationarity by incorporating projected changes in precipitation patterns into stormwater design should be considered as an important step. More research on SCM performance will provide approximation of the consequences of CC and will suggest how stakeholders might implement adaptive watershed protection strategies to adapt to these likely changes. This will also provide process-based information about pollutant transformations that can be utilized to develop new adaptation strategies for protecting water quality and ecosystem functionality. More work is also needed to estimate the degree of resiliency and reliability that management strategies provide under these nonstationary stressors. Watershed protection measures like urban SCMs often take several years to plan and implement, and even longer to reach their designed effectiveness, by which climate patterns may have changed and it is important that planners consider plausible future changes when designing and planning for these measures to attain water quality goals. These types of studies can assist water resources managers, local governments, decision makers, and watershed groups to evaluate the impacts of CC on urban communities. Predicting the impact of CC on stormwater infrastructure will help in better management of nutrients through implementation of SCMs, thereby supporting resilience and sustainability. Robust tools and frameworks are required to advance our ability to identify the most resilient and cost-effective management strategies that help simultaneously achieve

426 environmental, ecological, and economic goals in watersheds in the face of future CC. Such tools
427 and frameworks have the potential to transform how regulators, conservation personnel and
428 stakeholders respond to concomitant changes in water quality, climate, economics and land
429 management.

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Table 1. Summary of studies performed for assessment of runoff quality and quality under climate change

Literature Citation	Climate Model(s)	Time Period(s)	Climate Scenario(s)	Study Location(s)	Runoff Characteristics	Watershed Model(s)
Cameron (2006)	GCM, RCM	1961–1990, 2071– 2100	B1, B2, A2 and A1F1	Lossie catchment, Scotland	Flood depth and evapotranspiration	TOPMODEL
Semadeni-Davies et al., (2008)	RCAO, GCM	1994–2003, 2081–2090	A2 and B2	Helsingborg, Sweden	Runoff volume and peak runoff	MikeSHE and MOUSE
Franczyk and Chang (2009)	GCM	1973–2002, 2030–2059	A1B	Rock Creek basin, Portland, U.S.	Runoff depth	AVSWAT
Karamouz et al., (2011)	GCM	1990-2099	A2 and B2	Kajoo River, Iran	Floodplain extent	HEC-HMS
He et al., (2011)	GCM	1961–2000, 2010-2099	IS92a	Southern Calgary, Alberta, Canada	Runoff volume and peak flow, conductivity, turbidity, water temperature, DO and PH	ANN
Huong and Pathirana (2013)	GCM	1980–1999, 2020-2100	B1, B2 and A1F1	Can Tho City, Vietnam	Runoff volume	SWMM-Brezo
Borris et al., (2013)	GCM	2041-2070	A1B	Skelleftea, Sweden	TSS	SWMM
Stovin et al., (2013)	UKCP09	Baseline, 2031-2065	Medium emission scenario	NW Scotland, Sheffield, Cornwall, East Midlands, UK	Runoff volume, Evapotranspiration	Rainfall-runoff model
Zahmatkesh et al., (2014)	GCM	1981-2010, 2031-2065	RCP2.6, RCP4.5, RCP6.0 and RCP8.5	Bronx River watershed, NY, U.S.	Runoff volume and peak flow	TOPMODEL
Kirshen et al., (2014)	GCM	2011, 2040, 2070	A2, B1, A1B	The Winter Hill and Assembly Square watersheds, Somerville, MA, U.S.	Runoff volume and peak flow	SWMM

Wu et al., (2015)	RCM	2000-2009, 2050-2059	A2, and A1B	Stockholm, Sweden	Nitrogen and Phosphorus	GWLF
Borris et al., 2016	RCAO, GCM	2012-2013 2035-2064	RCP2.6, RCP4.5 and RCP8.5	Ostersund, Sweden	TSS, copper, lead and zinc	WinSLAMM
Dudula and Randhir, (2016)	GCM	1960-2006, 2035, 2065	RCP4.5	Ipswich River watershed, MA, U.S. Watershed	Runoff volume, baseflow	HSPF
Sharma et al., (2016)	GCM, RCM	2010-2011, 2100	A2	Hersted Industripark catchment, Denmark	TSS and Copper	STUMP
Wang et al., (2016)	GCM	Baseline, 2040-2059	RCP2.6, RCP4.5, RCP6.0 and RCP8.5	Outran Park and Jurong West, Singapore	Peak runoff, TSS, COD, TN and TP	SWMM
Alamdari et al., (2017)	GCM	1971-1998, 2041-2068	A2	Difficult Run watershed, VA, U.S.	Runoff volume, TSS, TN and TP	SWMM
Stonevičius et al., (2017)	GCM	1981–2000, 2081–2100	RCP2.6 and RCP8.5	Nemunas River basin, Lithuania	Runoff volume	WatBal
Jenkins et al., (2017)	UKCP09	1961–1990, 2020-2060	RCP 8.5	London Borough of Camden, London, UK	Flood damage	TUFLOW
Islam et al., (2018)	GCM	2014–2015, 2031–2050, 2081–2100	RCP4.5 and RCP8.5	Betna River, Bangladesh	<i>E. coli</i> and enterococci	MIKE21FM-ECOLab
Iqbal et al., (2019)	GCM	1990–2010 2040–2060, 2080–2100	RCP4.5 and RCP8.5	Kabul River, Pakistan	<i>E. coli</i>	SWAT
Alamdari et al., (2020)	GCM	1970-2000 2040-2070	RCP4.5 and RCP8.5	Difficult Run Watershed, VA, U.S.	Runoff volume, TSS, TN, TP	SWMM

GCM: Global climate model; RCM: Regional climate model; SWMM: Stormwater Management Model; SWAT: Soil and

Water Assessment Tool; HEC-HMS: Hydrologic Modeling System; WatBal: Water Balance; WinSLAMM: Source Loading and

Management Model for Windows; STUMP: stormwater treatment unit submodel for micropollutants; GWLF: Generalized Watershed

Loading Function; MOUSE: Model for Urban Sewers; ANN: Artificial Neural Network; RCAO: Rossby Center atmosphere- ocean

model; TUFLOW: two-dimensional unsteady flow; ABM: Agent based model; GFDL: geophysical fluid dynamic laboratory; SG WATER: smart growth water assessment tool for estimating runoff; IPCC: intergovernmental panel on climate change; RCP: representative concentration pathway; HSPF: hydrological simulation program Fortran; TOPMODEL: topography based hydrological model; UKCP09: UK climate projections 2009; DO: Dissolved Oxygen; COD: Chemical Oxygen Demand; TSS: Total Suspended Solids; TN: Total Nitrogen; TP: Total Phosphorus.

Table 2. Summary of studies performed for assessment of SCMs under climate change.

Literature Citation	Climate Model(s)	Time Period	Climate Scenario(s)	Study Location	SCM	Runoff Characteristics	Watershed Model(s)
Youn et al., (2012)	GCM	2001-2009, 2020-2042	A2	A four-story, Seoul, South Korea	Rainwater Harvesting	Storage capacity	Water balance model
Burge et al., (2012)	GCM	1990, 2030, 2070	B1, A1F1 and A1B	Melbourne, Australia	Raingarden, Swale, Tree pits, Wetland, Stomwater harvesting	Flow volume, TSS, TN and TP	MUSIC
Stovin et al., (2013)	UKCP09	Baseline, 2031-2065	Medium emission scenario	NW Scotland, Sheffield, Cornwall, East Midlands, UK	Green roof	Runoff volume, Evapotranspiration	Rainfall-runoff model
Hathaway et al., (2014)	GCM	2001-2004, 2055-2058	RCP 4.5, RCP 8.5	Nashville, and Rocky Mount, North Carolina, USA	Bioretention		DRAINMOD
Zahmatkesh et al., (2014)	GCM	1950–1979, 2030–2059	RCP 6.0, RCP 8.5	Bronx River watershed, NY, U.S. Watershed	Rainwater Harvesting, porous pavement and bioretention system	Runoff volume and peak flow	SWMM

Vanuytrecht et al., (2014)	GCM, RCM	1981–2010, 2031-2065	A1B	Flemish region, Belgium	Green roof	Runoff volume	GreenRoof
Lash et al., 2014	UKCP09	1961-1990, 2020-2040, 2040-2060, 2070-2090	A1FI	University of Exeter’s Environment and Sustainability Institute, UK	Rainwater Harvesting	Non-potable demand	PTST
Newcomer et al., (2014)	GFDL	2011–2012, 2099-2100	A1FI	San Francisco State University LID research network, San Francisco, CA, U.S.	Infiltration trench	Groundwater recharge rates and volumes	HYDRUS
Lo and Koralegedara (2015)	GCM, RCM	1981–2010, 2011–2099	A1B, A2 and B1	Colombo City, Sri Lanka	Rainwater Harvesting	Water security	Water balance model
Sharma et al., (2016)	GCM, RCM	2010-2011, 2100	A2	Hersted Industripark catchment, Albertslund, Denmark	Retention Pond	TSS and Copper	STUMP
Wang et al., (2016)	GCM	Baseline, 2040-2059	RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5	Outran Park and Jurong West, Singapore	Bioretention	Peak runoff, TSS, COD, TN and TP	SWMM
Thakali et al., (2016)	GCM, RCM	1971–2000, 2041–2070	A2	Flamingo and Tropicana watershed, Las Vegas, NV, U.S.	Detention pond	Runoff volume, storage volume	HEC-HMS
Borris et al., (2016)	GCM	2012-2013 2035-2064	RCP2.6, RCP4.5 and RCP8.5	Ostersund, Sweden	Grassed swale and biofilter	TSS, copper, lead and zinc	WinSLAMM
Haque et al., (2016)	GCM	1987-2014, 2020-2039	High emission scenario	Parramatta, Sydney, Blacktown, Richmond, Katoomba, Australia	Rainwater Harvesting	Water savings, reliability and water security	Water Balance Model
Joyce et al., (2017)	GCM	2004, 2006, 2012, 2030	A2	Cross Bayou Watershed , FL, U.S.	green roof, porous pavement, bioretention and retention pond	Peak flow, seepage outflow	TPXO and ICPR

Alamdari et al., (2018)	GCM, RCM	1971-1998, 2041-2068	A2	Hersted Industripark catchment, Denmark	Rainwater Harvesting	Water supply and runoff capture	RASP
Thakali et al., (2018)	GCM, RCM	1971-2000, 2041-2070	A2	Gowan Watershed of Las Vegas Valley, NV, U.S.	Permeable Pavement and green roof	Runoff volume, peak flow	SWMM
Kwon et al., (2018)	GCM	1971 to 2000, 2071-2100	RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5	Four metropolitan, South Korea	Rainwater harvesting	Storage volume	Simple Mass Balance equation
Kisakye et al., (2018)	GCM	1992–2012, 2025–2055, 2060–2090	RCP 4.5	Kabarole district, Rwenzori region, Uganda	Rainwater harvesting	Reliability	Daily water harvesting model
Wang et al., (2019)	GCM	Baseline, 2040-2059	RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5	Hypothetical catchment, Guangzhou, China	Porous pavement and bioretention	Runoff volume and peak flow	SWMM
Zhang et al., (2019)	GCM	1995–2004, 2040–2049	RCP 8.5	Melbourne Regional Office, Melbourne, Australia	Biofilter and Constructed wetland	Peak flow, TSS, TN and TP	MUSIC
Zhang et al., (2019)	GCM	1985–2015, 2020–2050	RCP2.6, RCP4.5 and RCP8.5	Yinchuan, Urumqi, Beijing and Fuzhou, China	Rainwater Harvesting	Water savings and stormwater capture	Water Balance Model
Giese et al., (2019)	GCM	2011-2016, 2045–2064, 2075–2094	RCP4.5 and RCP8.5	GI watershed and traditional watershed, Clarksburg, Maryland, U.S.	Bioretention, dry swale, grit separators, sand filters, dry pond, wet pond	Runoff volume	SWAT
Alamdari et al., (2020)	GCM	1970-2000, 2040-2070	RCP4.5 and RCP8.5	Difficult Run Watershed, Virginia, U.S.	Wet pond	Runoff volume, TSS, TN, TP	SWMM

RASP: Rainwater Analysis and Simulation Program; ICPR: interconnected channel and pond routing model; DRAINMOD:

drainage model; PTST: Probabilistic tank-sizing tool