A Synthesis of Climate Change Impacts on Stormwater Management Systems: Designing for Resiliency and Future Challenges

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Abstract: Climate change is projected to alter rainfall patterns in many parts of the US and around the world, highlighting the importance of stormwater management systems within resiliency efforts. Stormwater systems typically are designed based on historical rainfall records with the assumption of climate stationarity. This assumption is no longer valid for many locations, leaving a gap in the knowledge about how to ensure that these systems will meet the desired level of service over their design life. Researchers and practitioners have begun exploring how to incorporate future climate scenarios into the design of stormwater systems to maintain the current level of function well into the future. Despite this, uncertainty remains about how to manage cloudburst events, the water quality implications of climate change, and how to incorporate uncertainty in climate model outputs into engineering designs. In the absence of unifying design criteria for incorporating climate change into infrastructure design, communities have begun to form their strategies, from updating intensity–duration–frequency curves to characterizing rainfall based solely on "recent" historical data. As the debate continues regarding how to best protect communities against uncertain future weather patterns, a set of critical considerations has emerged. There is a dire need to explicitly define what resiliency means for stormwater management systems under a climate change paradigm to allow for clear design criteria that incorporate uncertainty and can achieve favorable outcomes at the system scale. There also is ample opportunity to develop new approaches and technologies that allow communities to optimize their infrastructure in terms of water management and an array of other ecosystem services. Thus, despite the current and future challenges of climate change, opportunities exist to develop the next generation of stormwater management systems that serve as multifunctional community assets. **DOI: 10.1061/JSWBAY.SWENG-533.**

Author keywords: Urban drainage; Green infrastructure; Climate change; Cloudburst events; Runoff; Stormwater control measures; Nonstationarity.

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Note. This manuscript was submitted on May 18, 2023; approved on October 5, 2023; published online on December 22, 2023. Discussion period open until May 22, 2024; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Sustainable Water in the Built Environment***, ©ASCE, ISSN 2379-6111.

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Introduction

As the impacts of climate change become increasingly evident worldwide, there is a critical need to better understand the practical implications of these changes on water resources in the built environment. Of particular concern are stormwater management systems (SMS), which are on the front line of changes in rainfall patterns and include stormwater control measures (SCMs) and associated gray infrastructure (pipes, structures, and so forth). Part of this concern has arisen as climate change renders one of the key facets of urban drainage design—that of a stationary precipitation frequency distribution—questionable at best (Rosenberg et al. 2010; Kendon et al. 2014; Deb et al. 2019). Changes in the precipitation distribution upon which infrastructure conventionally was designed essentially equate to changes in the risk that communities bear with respect to flooding, property damage, and human safety (Ganguli and Coulibaly 2017). Whereas natural watersheds evolve and adapt to changes in climate over time, effectively increasing flow capacity through channel evolution processes, fixed-dimension gray infrastructure does not inherently possess the ability to adapt. In typical urban stormwater networks, vulnerabilities such as flooding arise as the capacity of components within the system are overwhelmed and runoff accumulates at the surface or follows unintended paths. Studies to date indicate that the response of drainage systems to projected climate change is site dependent, and the capacity of some systems is predicted to remain adequate (e.g., Denault et al. 2002), whereas increased flooding and sewer overflows are predicted in other systems (e.g., Horton et al. 2010; Semadeni-Davis et al. 2008; Moore et al. 2016; Hettiarachchi et al. 2018). Furthermore, increases in watershed-scale runoff pollutant loads are projected under the impacts of climate change (Alamdari et al. 2020). SCMs historically have been used, in some cases for decades or generations, to alleviate the deleterious effects of urban hydrology on nearby water bodies and to reduce pollutants transported in stormwater (Hogan and Walbridge 2007). Although potentially a valuable tool for building resilience to climate change, these systems themselves also may be at risk of shifts in performance as new weather patterns emerge (Alamdari et al. 2020).

Climate change has several disruptive effects on SCM performance. These changes are highly spatially variable across large landscapes (Gao et al. 2012). For example, in the US, regions such as the desert Southwest, are anticipated to face prolonged droughts (USGCRP 2018), whereas the north-central and northeast regions of the US are projected to receive higher-intensity precipitation (USGCRP 2018). Temporally, changes in precipitation patterns across seasons also are expected, e.g., in the Great Lakes region (Hayhoe et al. 2010). Shifts in the precipitation phase from snow to freezing rain or rain also are expected as air temperatures increase (Tohver et al. 2014; Zaquot 2022). Other regions of the US (e.g., the Pacific Northwest and arid Southwest) are projected to experience minimal changes in typical annual precipitation, but rather significant increases in the frequency of extreme rainfall depths (Swain et al. 2018). In addition to precipitation depth, the intensity of events is expected to increase across much of the country (Tohver et al. 2014). Also relevant to SCM function is the dry-period duration (i.e., interevent period length) coupled with warmer temperatures which will add additional drought stress to the biotic components of these systems. Such elongated dry periods result in nutrient flushing in some types of SCMs due to microbial community disruptions and the breakup of soil aggregates (Manka et al. 2016).

Storm sewers, SCMs, and other urban drainage structures often are designed based on historical rainfall data, such as NOAA Atlas 14 (Perica et al. 2018), whereby specific storms of interest [e.g., a water quality event, a critical discharge-inducing event in a receiving stream (Hawley et al. 2016), or an infrequent return interval event] are used to inform the design characteristics of the system. Conventional approaches generally have not considered or integrated climate adaptation into designs, potentially resulting in underperformance over the long term. Many regulatory agencies also target specific pollutants of concern to be removed by SCMs, such as total suspended solids, nutrients, or heavy metals (WADOE 2019; MPCA 2022). The removal of specific pollutants in SCMs occurs through infiltration, filtration, biological processes, adsorption, and so forth, all of which can be substantially affected by changes in runoff hydrology, atmospheric conditions, and increased wash-off of pollutants from climate change–induced increases in rainfall intensity. In the age of climate nonstationarity, stormwater engineers and decision makers need to know (1) how current SMS and SCM designs will function under future climate scenarios, (2) what design modifications are needed (e.g., at a local or regional spatial scale) to ensure that SMS and SCMs are providing the desired level of service and are thus resilient to climate change, and (3) what factors are critical to consider regarding climate change. Herein, we summarize the state of knowledge regarding stormwater management in the US under climate change, identify design modifications to SCMs that have been explored, propose challenges that lie ahead, and provide a vision for the future. Although this article provides a US-centric perspective, it is known that similar performance challenges exist in international contexts.

Stormwater Management under Climate Change: The State of Knowledge

Enhancing the resilience, or the ability of a system to continue to function as expected in the face of change (Gersonius et al. 2012), of SMS through adaptive approaches is an area of active research. In particular, nature-based solutions can partially mitigate projected increases in surface runoff and flooding caused by climate change (Waters et al. 2003; Gill et al. 2007; Zahmatkesh et al. 2015; Moore et al. 2016). As a result, the stormwater management community now considers green stormwater infrastructure, including bioretention, green roofs, rainwater harvesting systems, and grassed swales, to be an integral component of adaptation planning (Gaffin et al. 2012; Hettiarachchi et al. 2022). Batalini de Macedo et al. (2021) referred to this as second-generation low-impact development (LID-2G).

In response, researchers have begun to examine the impacts of climate change on SCM performance at the site and watershed scales. Examples of research approaches for simulating future climate scenarios include change factor methods (in which scaling factors are applied to historical rainfall patterns), development of new design storm depths or intensities, modification of intensity–duration–frequency (IDF) curves, rainfall disaggregation or downscaling techniques, and statistical models, often coupled with urbanization or development scenarios (Barah et al. 2021; Moore et al. 2016; Rosenberger et al. 2021; Semadeni-Davis et al. 2008; Tirpak et al. 2021; Wang et al. 2019; Zahmatkesh et al. 2014; Zhang et al. 2019). The performance of several SCMs has been modeled using climate change projections, including bioretention (Hathaway et al. 2014; Winston 2016; Tirpak et al. 2021), permeable pavement (Liu et al. 2015; Smolek 2016), green roofs and walls (Barriuso and Urbano 2021; Vanuytrecht et al. 2014), rainwater harvesting systems (Tavakol-Davani et al. 2016), constructed wetlands (Zhang et al. 2019), and retention ponds (Sharma et al. 2016). Although some studies found minimal effects on SCM function (e.g., Zahmatkesh et al. 2015), many studies reported diminished performance for SCMs designed using existing design criteria under future climate conditions (as discussed subsequently). Designing larger SMS or including other potential factors of safety may suffice for maintaining performance and may buffer against uncertain future climate conditions (Liu et al. 2015; Tirpak et al. 2021; Zhang et al. 2019); however, such modifications likely will result in increased costs and additional use of land for stormwater control.

Climate change impacts on SMS performance depend on several factors, including SCM type, design approach, drainage area characteristics, and associated treatment processes. For example, runoff volume reduction, peak flow mitigation, and water quality treatment provided by bioretention facilities all will be impacted by changes in climate. Temporary surface storage zones, which often are sized based on historic rainfall records, may be overwhelmed more frequently by forecasted larger, more intense rain events, resulting in more frequent untreated stormwater and occasionally wastewater flows (i.e., in combined sewer overflow watersheds) bypassing treatment (Olsson et al. 2009; Hathaway et al. 2014; Winston 2016; Alamdari et al. 2020). Similarly, prolonged dry periods between rain events coupled with increased air temperatures may stress plants and microbial communities that remove pollutants via uptake and microbially mediated processes, such as denitrification (Fowdar et al. 2021). Even successful runoff capture may result in management challenges; for example, increased runoff volumes retained following projected extreme events could lead to more localized groundwater mounding, which may impact adjacent infrastructure (Machusick et al. 2011).

SCM Design for Climate Change

In response to current and future shifts in climate, the stormwater management community has begun to evaluate strategies that will improve SCM resilience. These design alterations are to either the physical properties of SCMs (e.g., depth of ponding, the ratio of watershed area to SCM surface area, vegetation type, and so forth) or the hydrologic design criteria of SCMs (e.g., increased design storm size, designing based on recent storms of concern, and so forth). These responses are not mutually exclusive, and mitigation strategies are likely to employ both categories. These design changes also will impact water treatment, because it is linked inextricably to SCM hydrologic function.

The magnitude of changes to SCM design characteristics may depend on the severity of climate change for a given region. Locations at which these changes are projected to be greater may require more-intensive adaptations (e.g., larger storage volumes, deeper filters). For example, Hathaway et al. (2014) found that bioretention surface ponding depth in North Carolina would need to be increased by a factor of approximately 1.7–2.7 to limit overflow volume under climate change to that of the current climate. Cook et al. (2021) observed substantial (~30%–50%) decreases in runoff reduction for bioretention systems under climate change projections for Memphis, Tennessee, and for Pittsburgh. Although many locations may not require extreme design interventions, sizable design changes could be necessary for some locations depending on the desired level of service. Conversely, minimal deviations from current design practices may be sufficient in areas in which minimal changes are forecasted (Weathers et al. 2023; Winston 2016). Further complexity is added by site-specific conditions, which also may drive adaptations required for infiltration-based SCMs. For example, extensive design modifications may be required for SCMs installed over poorly draining soils, whereas existing designs installed atop rapidly draining native soils may still provide adequate treatment under future conditions. Furthermore, temperature-related variability in the performance of infiltration-based SCMs (i.e., higher recession rates in warmer months) has been observed in some regions (Ebrahimian et al. 2020), and can be leveraged for optimizing the SCM design as the climate warms (Ebrahimian et al. 2021). However, the infiltration dynamics may change in different regions depending on the severity of climate (temperature) change. Real-time control of SCMs, which may adapt the storage capacity, detention time, and peak outflow rate of SCMs based on forecasted weather, is another means to manage changing amounts of rainfall that are associated with climate change (Brasil et al. 2021; Persaud et al. 2019). However, real-time control of SCMs is not a silver bullet; there are limitations in the ability to adapt SCM performance using real-time control, because their original design specifications remain static.

The second category of adaptations is related to the design criteria utilized for SCMs. The stormwater management community lacks an organized, globally accepted approach to sizing and design criteria, leading to varying climate-based modification approaches across communities worldwide. Notably, efforts are underway to provide more standardized specifications and testing through the ASTM E64 Committee on SCMs, which may include climate-based modifications for different types of SCMs (ASTM 2022). Regardless, substantial and specific actions are being taken by designers to adapt to the effects of climate change (Table 1). These approaches vary, but examples include utilizing climate model projections of future conditions to update IDF curves, considering recent extreme events in modeling and design, and evaluating high-intensity events and the accompanying shift in rainfall intensities for the design event (Mailhot and Duchesne 2010).

Challenges That Lie Ahead

Cloudburst Events

One of the most prevalent concerns for SCMs, which are critical elements of SMS, is anticipated increases in precipitation magnitude and intensity in many regions. This increase is driven by an increase in air temperature and associated atmospheric moisture holding capacity; this relationship is intensified further in convective systems associated with thunderstorm or cloudburst rain events (Berg et al. 2013; Hayhoe et al. 2018). Cloudburst rain events are described broadly as high-intensity, short-duration rain events, and analogous terms include downpour, torrential rain, and water or rain bomb (Rosenzweig et al. 2019). Definitions of cloudburst events vary; in New York City and Rotterdam, the 100-year design storm defines a cloudburst event (NYCDEP 2017), whereas meteorological guidance for cloudbursts typically is an intensity exceeding 100 $\mathrm{mm\,hr^{-1}}$ (AMS 2012). The recent increase in frequency of cloudbursts indicates a diversion from stationarity. Runoff from these high-intensity events can quickly exceed the surface storage capacity of SCMs or the surface infiltration rates of infiltration-based SCMs. They can cause significant flood events, such as that in Ellicott City, Maryland, which experienced 168 mm of rain in less than 3 h in both 2016 and 2018 (Doheny and Nealen 2021). Design storms historically used for flood control SCM design in many communities are 24-h events with a specific recurrence interval based on a statistical analysis of historical precipitation depths and durations consistent with their region's Soil Conservation Service (SCS) rainfall distribution. The standardization of 24-h rainfall duration for design also contributes to inadequate flood control for these shorter-duration, high-intensity events. Systems designed with such criteria are woefully

Table 1. Modifications to SCM design criteria currently employed by communities

Approach	Description	Example communities
Recent extreme storms	Use recent flooding or extreme precipitation events as part of the design process.	Lexington-Fayette Urban County Government, Kentucky; Arlington County, Virginia
Nonstationarity rainfall statistic	Update rainfall statistics from observed records that are adjusted to account for nonstationarity.	Illinois State Water Survey
Level of service	Adjust the level of service design standards as a surrogate for changing rainfall. This could involve changing the target recurrence interval for a conveyance or storage practice (e.g., designing detention for a 50-year instead of a 25-year storm). Additional safety factors could be added, for example, providing 1 m of freeboard on a detention basin instead of 30 cm.	Madison, Wisconsin (level of service change); Copenhagen, Denmark, and New York City (cloudburst management); Washington, DC (considering adding a cloudburst approach)
Uniform percentage increase	Increase rainfall depth or intensity by a constant amount to account for future rainfall predictions.	Virginia Beach, Virginia (increased design rainfall intensities by 20%).
Future rainfall projections	Develop future rainfall projections for the design of infrastructure projects. This may include updates to NOAA Atlas 14 intensity-duration-frequency curves for future scenarios and existing conditions. A core principle is that drainage infrastructure is sized for a given design or useful lifespan utilizing the predicted rainfall amount at the end of the design or useful life.	District of Columbia; Boston; New York City; Cambridge Massachusetts; Seattle; King County, Washington; Arlington County, Virginia; Alexandria, Virginia; Wilmington, Delaware; Lancaster, Pennsylvania; Miami-Dade County, Florida; and Jacksonville, Florida
Temperature-based	Future rainfall projections are based on projected average annual temperature changes. This results in changes to the amount and distribution pattern of rainfall.	Auckland, New Zealand and Australia
Risk-based	Adaptive design and risk-based approaches consider the consequence and likelihood of large rainfall events when selecting the hydrologic design standards for a site or project. Typically, critical infrastructure projects (e.g., wastewater and drinking water treatment plants, hospitals, and emergency access routes) are designed for a higher level of service, higher confidence interval, or a larger factor of safety for elements where the consequence of an event (rainfall) is higher.	Washington, DC; Boston; New York City; WSSC (Washington Suburban Sanitary Commission) Water; Montgomery County, Maryland; Mexico Beach, Florida; Caño Martin Peña, San Juan, Puerto Rico; and Hurricane Sandy Recovery Projects

underprepared for the observed increased occurrence of cloudburst events (Berg et al. 2013), because these types of events were not as common or sometimes were not observed in the historical records used to develop IDF relationships.

Water Quality

Climate change affects water quality in many ways. For example, in some regions there will be increases in interevent duration, which would lead to an increased build-up of pollutants between events on watershed surfaces, and would impact the biogeochemical processes within SCMs that remove pollutants (Hatt et al. 2007; Manka et al. 2016). Additionally, there have been observations of increased whiplash weather—rapid changes in weather conditions such as temperature swings or erratic rainfall (i.e., from drought to above-normal precipitation) which can increase pollutant loading exports downstream (Loecke et al. 2017). Increases in high-intensity events also may wash off greater masses of some pollutants (such as sediment) which can affect SCM function. As an example, accelerated clogging and reduced infiltration capacity in filtration and media-based SCMs could increase maintenance needs as increased sediment washes off and accumulates over the top of and within pore spaces. Changes in types of precipitation (e.g., freezing rain becoming more common than snow) also may lead to increased deicer application in certain regions; which could cause concern because deicing salts can reduce retention of metals and nutrients in SCMs (Kakuturu and Clark 2015; Søberg et al. 2017; McManus and Davis 2020; Kinsman-Costello et al. 2022), cause mobilization of sediment and compaction of SCM soils due to changes in soil chemistry (Winston et al. 2016), and/or result in negative impacts on soil physical properties in filtration-based SCMs.

Coastal Systems

Urban coastal areas are among the world's most vulnerable landscapes; they are affected by climatic and anthropogenic perturbations that include multiple storm pathways, such as hurricanes, sea level rise (SLR), and excessive pollutant loads (The Nature Conservancy 2020). SLR is a result of climate change, and is a unique confounding factor for coastal SMS. Urbanization and land development coupled with shallow water tables, limited topography and gradients, tidal influence, and saltwater intrusion can create major challenges in adequately managing urban runoff and terrestrial pollutant loads in coastal cities (Gold et al. 2022). Changing precipitation patterns have exacerbated the impacts of these phenomena, leading to increased risks for people, property, and infrastructure. Low-lying coastal areas are particularly vulnerable to SLR, because the outlet elevations of SMS are fixed, and more frequently are becoming partially or completely submerged, leading to regular inundation of sewer networks, and creating prolonged tailwater conditions. The loss of this in-line capacity and necessary additional hydraulic head to generate sufficient conveyance decrease the SMS level of service and increase flood occurrence, particularly from short-duration, high-intensity (cloudburst) events that would have been managed sufficiently by available in-line storage within a drained network.

Uncertainties remain due to limited knowledge regarding SCM performance in urban coastal areas and how performance changes in response to climate change effects (Sussams et al. 2015;

Idiata 2016). Understanding the performance of SCMs in coastal environments is particularly challenging because of the integrated effects of SLR (e.g., groundwater level shoaling and tidal impacts), extreme rainfall events, and coastal inundation (Rahimi et al. 2020). Therefore, an investigation into the performance of these various defenses both individually and in conjunction to optimize their efficiency will be critical in decision-making and planning to protect vulnerable coastal cities.

Additional Resource Requirements

SCM costs (both capital and life cycle) and funding gaps also can be greatly affected by climate change and increased hydrologic variability. Regions with increased runoff volumes may need to increase SCM storage and perform more-frequent maintenance, whereas regions with reduced runoff volumes may require advanced designs to increase water retention and account for difficult scenarios such as increased dry weather and reduced base flows. Furthermore, underserved communities already face increased health risks as a result of a lack of funds or disinvestment in SMS. Communities may struggle to evacuate for extreme events (e.g., hurricanes, floods) that pose a direct threat to their health and property (Parkinson 2003). Underserved communities often deal with multiple disproportionate injustices to their water infrastructure, making them vulnerable to natural hazards (Hendricks and Van Zandt 2021; Wilson et al. 2008; Fernandez-Bou et al. 2021). The current annual funding gap for SCMs is estimated to be as high as $8.5 billion annually in the US (WEF 2021). These gaps will be exacerbated by (1) the need to adapt SCMs for climate resiliency and (2) disparities in communities in which the vulnerability is highest.

Climate Models: Data Resolution and Alternatives

Future climate projections recently have been paired with hydrologic and hydraulic models to determine how urban drainage infrastructure performance may be affected by climate change (Moore et al. 2016; Alexander et al. 2019; Sharma et al. 2021; Hettiarachchi et al. 2022). Such efforts are increasingly possible as data become available in public repositories (e.g., NA-CORDEX and LOCA). Furthermore, downscaling of global climate models has brought increased granularity to projections, and data now commonly are available at spatial scales that allow more-targeted local planning (Gao et al. 2012). Despite this, the temporal scale of data remains a challenge for SMS. This is particularly the case for many SCMs in which small catchments or drainage areas have short times of concentration (e.g., ≤5 min in some cases). Conversely, the highest temporal resolution climate projections present in the aforementioned public repositories typically are no finer than hourly; improved methods for subhourly hyetograph estimation are needed (Joyce et al. 2017). This mismatch in time scales limits the accuracy of these approaches for simulating urban landscapes, particularly as it relates to the simulation of hydrograph shapes and peak flow rates.

Another concern is the uncertainty associated with both the magnitude of human actions to curb emissions and the implications of model selection and downscaling approaches. The former traditionally has been handled through the development of various Representative Concentration Pathways (RCP), which are various possibilities for future emissions based on human interventions (or lack thereof). These RCPs can be utilized in global climate models to present various potential future conditions.

In terms of model selection, there are numerous global climate models (GCMs) that differ in their representation of fundamental processes, resulting in different predictions for a given location. Furthermore, multiple approaches are used to downscale global climate models to allow more localized predictions. Approaches range from statistical downscaling to dynamical downscaling using regional climate models (RCMs), of which there are many. Because of this assortment of possible future climates for a location of interest (i.e., combinations of GCMs and RCMs), many studies used ensemble approaches to allow an understanding of the range of possibilities. These methods are likely to continue to be popular, and error bands and uncertainties will be presented along with the most likely outcomes. Such methods recently have been developed for informing future urban stormwater management projects in the Chesapeake Bay, with the Projected Intensity-Duration-Frequency (IDF) Curve Tool for the Chesapeake Bay Watershed and Virginia (Miro et al. 2021). It is understood that uncertainty increases for more-extreme precipitation events, which cascades into impacts on SMS design (Lopez-Cantu et al. 2020). For example, selecting design storms near the upper bounds of uncertainty can result in more than a twofold increase in stormwater infrastructure design costs (Cook et al. 2020).

Moving Forward

Climate change poses a substantial threat to communities worldwide, leading to increased weather extremes that can overwhelm SMS. Stormwater drainage infrastructure lies at the front line of these impacts, but also is key to cities becoming (more) climate resilient. To achieve the desired level of service, modern and innovative design standards and techniques will be needed. In addition to utilizing increasingly available future climate projections to inform designs (such as the examples in Table 1), several additional factors and approaches that are now essential to incorporating climate change into stormwater management are as follows:

- Get comfortable with uncertainty

  The stormwater management community has recognized uncertainty for quite some time. However, quantifying uncertainty is different than incorporating it into decisions. Approaches for planning under uncertainty have been utilized for decades in numerous contexts (e.g., finance and power systems), yet only recently have been explored for SCM design under climate change (Ramshani et al. 2020; Barah et al. 2021; Webber and Samaras 2022). Such methods should be integrated into long-term planning to produce robust and resilient solutions against a changing climate and the range of potential future conditions discussed herein. Furthermore, uncertainties and relative risks must be communicated to decision makers and stakeholders, allowing a more informed and inclusive planning process. In previous decades, engineers and planners accepted a level of risk (which was assumed to be known under climate stationarity) through the use of design storms. However, awareness of the linkage between design criteria and risk has eroded over time; and although risk cannot be eliminated, it can be reduced. Thus, communication about risk must return to the forefront of education and design; that is, when given design criteria are chosen, there are inherent risks in those criteria that must be communicated, understood, and internalized by the designer, and subsequently addressed in the final design. Additionally, it is critical to embed flexibility and adaptive capacity into decision-making processes, and to adapt more quickly as new information becomes available.
- Think at the system scale

  Viewing the stormwater network as a system is imperative in order to truly understand the implications of upland management on in-stream conditions (ecology, flooding, and so forth). Petrucci et al. (2013) indicated that uncoordinated parcel-scale implementation of stormwater management can aggregate at the watershed scale in ways that have unintended consequences. In particular, when urban flash flooding is a concern, investigating the implications of parcel-scale SCM installations on the watershed scale will be increasingly important in the future, and can lead to more successful outcomes. Coordinated, systematic implementation of SCMs in a watershed is necessary to achieve the desired outcomes related to reducing the urban stream syndrome and improving receiving water health. Optimizing SCM siting from a system perspective can maximize function and benefits from limited resources (i.e., funds and land area) while helping achieve flow-regime objectives for baseflows and stormflows, and water quality goals. System-scale thinking also can lead to better-integrated water-cycle management in which stormwater can be utilized, to the extent feasible, as a component of the water supply.

- Use multifunctional landscapes

  Communities should evaluate how to build redundancy into urban drainage systems, particularly by considering a diverse suite of SCMs. Green stormwater infrastructure SCMs should be designed for water quality events with appropriate bypasses or overflows that ensure that these SCMs will not be washed out during extreme events. Larger, centralized SCMs then can be implemented for flood control and resiliency. These larger facilities may include safe to fail features for more extreme scenarios in which infrastructure generally serves a primary purpose other than stormwater control (e.g., recreation) but also is designed to be flooded during extreme events (i.e., multifunctional landscapes). For example, New York City and Copenhagen, Denmark, have piloted cloudburst planning that incorporates some safe to fail solutions such as parks and basketball courts that are designed to flood periodically but that serve other functions (e.g., recreation and public open space) at other times. Nonprofit groups have partnered with city agencies to retrofit public school playgrounds as multifunctional stormwater parks, utilizing porous pavement, detention, and bioretention SCMs embedded within play areas in New York City (Trust for Public Land 2022).

- Incorporate technology

  Adapting to climate change is not solely structural. Maintenance is critical to combating urban flooding from extreme weather; it ensures that stormwater assets are functioning optimally and that their full storage capacity is available. The capacity of existing SMS likely will be met or exceeded more frequently under climate change. Although appropriate maintenance during the life of a SCM is imperative, maintenance often has been inconsistent; this is because it might be labor-intensive or costly, the methods might not be clear or consistent across SCM types, or comprehensive and customizable maintenance guidelines are lacking (Erickson et al. 2018). The need to rethink and improve SCM maintenance by adopting a dynamic, risk-based, and data-driven framework was suggested by Wadzuk et al. (2021b) and elaborated on by Wadzuk et al. (2021a). Made possible through rapid advancements of the Internet of Things (IoT) and sensor technologies, data-driven maintenance will assist with identifying important factors that cause failure in stormwater systems; furthermore, these technologies can help to optimize maintenance activities, in turn reducing failure risk and minimizing associated costs.

  Likewise, technological advancements have allowed an unprecedented amount of information about overall stormwater system function in real time. Such information has ushered in the concept of smart stormwater systems that are not only capable of reacting to current conditions but can anticipate future conditions and adjust proactively (Kerkez et al. 2016). This proactive function in SCMs, in particular those with large storage amounts, such as wet ponds, may aid in providing additional storage before extreme events (Erickson et al. 2022). This use of technological advancements may allow more efficiency in existing infrastructure (that was designed based on historical rainfall trends), alleviating the need for cost-prohibitive replacement or refurbishment of undersized assets.

- Quantify SCM resilience goals

  As future climate projections become increasingly easy to access and use, efforts to understand the impacts of climate change on stormwater infrastructure are expanding. However, to move from knowledge to action, it is imperative to rethink SCM design approaches and consider new climate patterns. It is imperative that the stormwater community collectively overcomes the inertia required to update policy and standards at all levels. Communities are independently modifying design guidance to address climate change (Table 1). Although these efforts are laudable, clear guidance from professional societies and regulators would be invaluable to allow a more unified approach (while maintaining local context) at the regional, national, and international scales while maintaining local context. Furthermore, updates to critical data sets, such as NOAA Atlas 14, are central to better understanding current conditions and the accuracy of climate projections.

Currently, many approaches presented in the literature (i.e., Hathaway et al. 2014; Tirpak et al. 2021) and in Table 1 rely on design changes to maintain the same level of performance in the future as has been provided historically. For example, this has taken the form of maintaining the same frequency of overflow for bioretention, increasing the size of design storms based on future conditions, and so forth However, additional considerations should be made to determine whether historical design criteria can achieve the level of resiliency desired by communities. From this, critical philosophical questions arise that should guide stormwater management over the coming decades:

1. What does it mean for a stormwater system to be resilient?
2. How can we quantify this desired level of resilience (site-based and watershed scales)?
3. How can historical approaches to stormwater infrastructure design (24-h design storms, parcel-scale stormwater management, and so forth) provide this resilience?

These are the questions that stormwater professionals will wrestle with in the coming decades as climate change and its effects are realized around the world.

The legacy of twentieth-century stormwater infrastructure largely has been one of inadequacy, because stormwater remains a leading cause of impairment for many US waters and nearly all urban or urban-adjacent waters (Walsh et al. 2005). Current and future stormwater professionals can create a different legacy for the 21st century and beyond. Climate change is no longer on the horizon—it has arrived and will continue to come ashore, overloading our infrastructure more and more frequently. However, the strategies and tools included here provide a guide to the profession for moving forward in the face of change that may last as long as careers. Like the communities that are served, stormwater professionals must adapt to climate change while it is happening.

Data Availability Statement

No data, models, or code were generated or used during the study

Acknowledgments

This article was prepared by members of the American Society of Civil Engineers Urban Water Resources Research Council (UWRRC)'s Climate Change Subcommittee who collectively recognized the need to aggregate resources for stormwater professionals tackling the unique and varied challenges presented by climate change.

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