Bioretention Design Modifications Targeting Climate Resiliency

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Highlights

- Climate change challenges green infrastructure designed assuming climate stationarity
- Simulations show amended bioretention designs may be resilient to future climate changes
- Increasing surface area yielded greater returns over conservative design changes

Introduction

Cities around the world are increasingly turning toward green infrastructure (GI) stormwater control measures (SCMs) to mitigate the effects of urbanization and land development on receiving water bodies and aquatic ecosystems. A growing body of research has demonstrated the ability of bioretention cells, one such SCM, to reduce runoff volumes and mitigate peak flow rates to levels that resemble pre-development hydrologic conditions. Bioretention designs are often based on past climate patterns, where treatment objectives (e.g., retaining runoff from the 90th percentile storm on-site) derived from historic records are used to determine key parameters such as surface area. Deviations from historic conditions, such as those associated with climate change, challenge this approach and threaten to overwhelm existing systems, risking diminished performance and/or operational failure. Given their operational lifespan, the function of presently installed SCMs in future climate conditions is uncertain.

Climate change studies rely on future projections based on outputs from general circulation models (GCMs), the outputs from which are frequently downscaled using a variety of methods, such as regional climate models (RCMs) to meet the fine spatial and temporal scales suitable to urban hydrologic assessments. Past studies have relied on several techniques to assess climate impacts on GI, including delta change factors, augmented design storms, and numerical models (e.g., Wang et al., 2019, Zhang et al., 2019). Results have ranged from improved performance in future scenarios where GI is implemented at the watershed scale to recommendations for larger practices in order address the large variability that exists between climate projections. As climate change impacts are highly regional and uncertain, and the mixed results of previous studies, there is a need to examine the function of these systems in future conditions. Further, there is a need to investigate methods to build climate resiliency into bioretention design and determine how specific design elements impact performance under uncertain climate conditions. The objective of this study was to characterize bioretention function under multiple climate scenarios to that of a baseline period and identify the design modifications that must be implemented to achieve past performance under future conditions.

Methodology

Hydrologic Model and Bioretention Design Configurations

The study focused on a hypothetical catchment located in Knoxville, Tennessee, USA, which consisted of a completely impervious, 0.4 ha area draining to a single bioretention cell. Models were constructed using USEPA SWMM 5.1 to assess bioretention performance under future conditions. Model scenarios were simulated between 2040-2044, representing the final five years of a 25-year service life for a bioretention cell constructed in 2020. To test the effects of design variations on future performance, components were modified beyond baseline recommendations in local regulations. This was achieved by altering parameters such as surface storage depth, media depth, media conductivity, and the surface area of the bioretention cell, yielding fifteen design configurations in total. The effect of site conditions was examined by testing three underlying soils, ranging from clay (K1) to sandy loam (K3).

Climate Change Projections, Bias Correction, and Performance Analysis
Ten dynamically downscaled projections of hourly rainfall data for 2040-2044 were downloaded from the North American Coordinated Regional Downscaling Experiment (NA-CORDEX) Program and served as inputs to hydrological models. Kernel density distribution mapping (KDDM), a novel non-parametric technique developed by McGinnis et al. (2015), was implemented to correct climate model bias using the "climod" package for the statistical software, R. Three components of the annual water balance (surface overflow, infiltration, and drain outflow) were used to compare future (2040-2044) bioretention performance against levels achieved under past climate conditions, characterized from simulations performed using observed climate data from 2010-2014.

Results and discussion

Simulation results are presented in Figure 1, where design configurations are listed from 1 (lowest deviation from current practice) to 3 (largest deviation). For example, DEP1, DEP2, and DEP3 represent design configurations where media depths were increased from 15cm (DEP1) to 122cm (DEP3). Configurations where surface storage depths (P, ranging from 15-61cm), media conductivity (CON, 51-102mm/hr), and bioretention surface area (A, 5-15% of the contributing drainage area) were modified followed similar trends, while LOW, MID, and HIGH represent a combination of these parameters (Figure 1). Results demonstrate that current designs may be sufficient under future scenarios that represent lower deviations from current climate but are overwhelmed in others. Further, the effects of site-specific conditions on bioretention performance were evident, with an increased number of designs surpassing historic annual infiltration volumes under future conditions when underlain by well-drained, sandy loam soils (K3) compared to clay or clay loam soils (K1 and K2, respectively). This suggests that more conservative design amendments (e.g., deeper media layers, increased temporary ponded storage) could have greater impacts at sites with moderate to well-drained *in situ* soils compared to poorly drained soils, where more significant modifications (e.g., increasing surface areas or implementing several modifications simultaneously) are needed to meet past performance. Unlike infiltration and drain outflow, which was similarly affected by site conditions, underlying soil properties had little effect on annual surface overflow. Because this represents runoff that bypassed any treatment or hydrologic mitigation, it may be an indication that more significant modifications are needed, such as the larger practice sizes, deeper media depths and increasing surface storage, to reduce future runoff impacts regardless of site conditions.

Depending on management objectives, risk tolerance, and site conditions, results illustrate where priority should be placed to foster resiliency to changing climates. For example, if the primary management objective was to reduce runoff via infiltration from bioretention cells atop poor to moderately drained soils, increasing the media layer depth was shown to provide greater returns compared to other conservative design modifications (e.g., increasing ponding depths or media conductivities) (Figure 1). Conversely, increasing ponding depths (P) provided the greatest improvement to infiltration performance for sites with well-drained soils (K3). However, regardless of underlying soils, increasing bioretention surface area relative to the catchment had the largest effect on future performance, a finding supported by studies investigating the impact of climate change on GI (Wang et al., 2019; Zhang et al., 2019). Increasing bioretention surface area from 5% to 15% of the catchment (configurations A1 and A3, respectively) resulted in all scenarios surpassing historic infiltration performance. This effect was especially pronounced in simulations using poorly draining underlying soils (K1). Increasing bioretention surface area also led to the largest improvements with respect to minimizing surface overflows, which represent unmitigated runoff that bypassed treatment provided by the system. This suggests that expanding bioretention surface area in new installations may become increasingly important under future climates, especially in sites with poorly drained native soils.

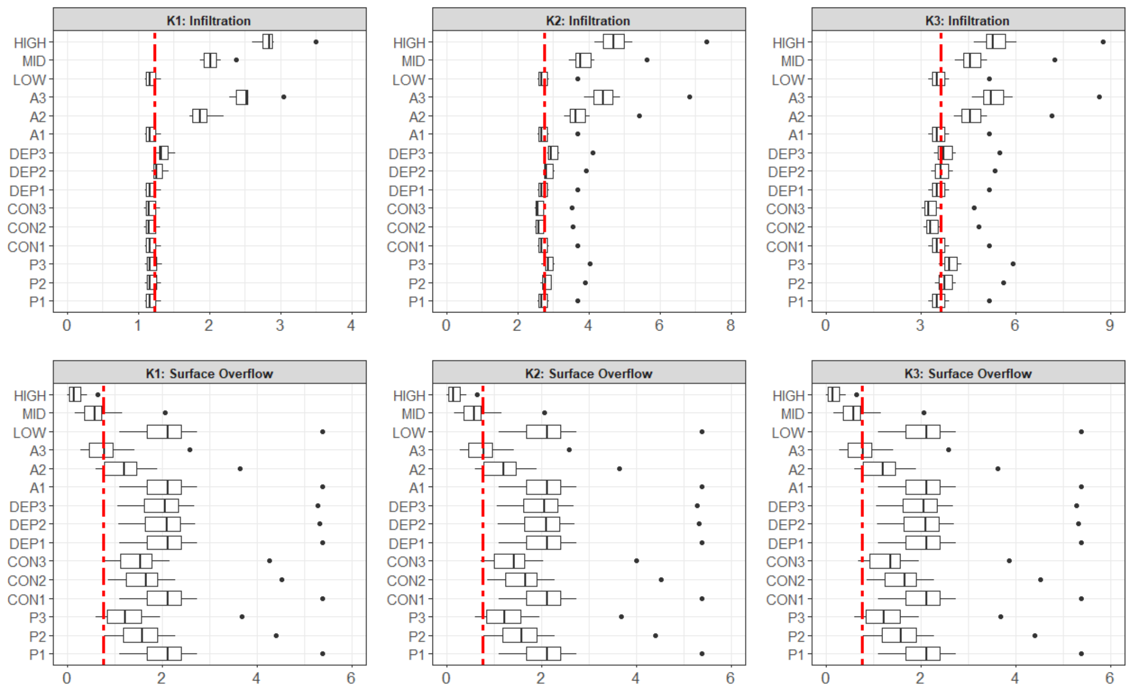

Figure 1. Boxplots depicting annual infiltration and surface overflow volumes (1000 m^3/yr) from simulations of ten future (2040-2044) climate projections using various design configurations under three underlying soil conditions (K1: clay; K2: clay loam; K3: sandy loam). Performance under current standards and 2010-2014 climate data shown in dashed, vertical red lines.

Conclusions and future work

Using a probabilistic approach, hydrologic simulations of a hypothetical, completely impervious catchment using varying underlying soil characteristics were analyzed to evaluate the efficacy of design modifications to add resiliency to bioretention cells in the face of future climate uncertainty. Results indicated that the greatest performance returns occurred when increased surface areas (relative to the contributing catchment) are used in design, especially in sites with moderate to poorly drained *in situ* soils. Future studies should implement this methodology with a larger set of climate models and study locations to better understand the localized impacts of climate change on bioretention performance.

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