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Unveiling the hydrologic climate resilience of Blue Green Infrastructure: Do we have our design/modelling numbers right?

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Abstract
As precipitation patterns change, so does the need for revised Blue-Green Infrastructure (BGI) design standards. Holistic hydrologic design and modelling are vital for addressing climate uncertainties and ensuring the long-term integrity of optimized BGI. Within that scope, two key design needs are what size storm event needs to be safely routed through a BGI practice, and what is the precipitation depth of a Water Quality (WQ) event? WQ events principally determine the surface area and storage depths of BGI. The investigation uses North Carolina, USA, as a case study to determine revised design standards for these hydrologic parameters. Of particular interest was the increase, usually substantially (up to 25%), required for the WQ event depth when focusing on the most recent decade of available precipitation data. These results will be used to inform design standards in NC, likely yielding larger, and more protective, BGI in the coming years.

Highlights
- The importance of developing a holistic methodology to include past and future storm values.
- High-quality weather data series and intervals inform better design and modelling.
- Climate change is already affecting BGI design/modelling in NC (underestimates WQ event).

Introduction
Surface runoff and its associated precipitation are the main factors driving the hydrologic performance of Blue-Green Infrastructure (BGI), aka Stormwater Control Measures (SCMs) in the USA, and Sustainable Urban Drainage Systems (SUDS) in Europe (Fletcher et al., 2015). Climate change projections indicate an increase in the frequency and intensity of extreme weather events, particularly severe precipitation (IPCC, 2022). This trend is likely to heighten socio-economic vulnerabilities in urban areas, threatening critical infrastructure and degrading urban ecosystems (Zheng et al., 2024). In this vein, Hathaway et al. (2024) stressed the importance of a comprehensive design scheme for BGI, updating essential design variables informing design and modelling, such as the Intensity-Duration-Frequency (IDF) curves and the water quality (WQ) storm event, in order to define the present and projected runoff volumes that BGI techniques will need to accommodate to avoid

performance failure. These updates consequently affect the choice of surface areas, cross-sections and materials used in the design of certain BGI practices. Effectively addressing stormwater challenges linked to climate change necessitates targeted regional and local analyses of precipitation patterns to enhance our understanding of rainfall dynamics (Nodine, 2024). Nguyen and Nguyen (2020) proposed a spatio-temporal statistical downscaling method for modelling extreme rainfall, establishing a connection between Global Climate Models (GCM) and local projections relevant to small urban watersheds. Previous studies conducted by Alamdari & Hogue (2022), and D'Ambrosio et al. (2023) further illustrated that performance metrics declined with heightened rainfall extremes, prompting recommendations for retrofitting and flexible design. In this context, this article aims to develop a holistic methodology to design long-term BGI practices based on up-to-date and realistic design variables (i.e., WQ storm event and IDF curves). North Carolina (NC), USA, was chosen as the case study as it has required BGI to be installed since the 1990s, and now has tens of thousands of SCMs implemented across the state (Mitchell, 2024). Then, the state has since experienced record-breaking rainfalls and floods that have cost the citizens millions of dollars, displacing many from their homes. This is a state where designers are "hungry" for BGI design guidance that reflects the current reality, rather than that based on precipitation patterns for the previous 40-50 years. One particular design parameter of interest is the (WQ) storm event. This is the rainfall depth that BGI is required to treat the runoff from. Using long-term data, this value was calculated to be approximately 25 mm (1 in.) for much of the state (mainly the Piedmonts and the Mountains-Western; Cfa and Cfb, respectively; based on Köppen-Geiger's climatic classification), and 38 mm (1.5 in) for coastal NC (Coastal Plains; Cfa). This research provides an update on those variables, answering the question of whether we have our numbers right or if we need to move on to different values and current methods considering climate change at their core. As the WQ storm event directly affects the surface area and storage depths of BGI, this research will impact the need to rethink the materials and cross-sections commonly utilized in BGI practices, as well as their surface area occupation.

Methodology

The methodology is divided into two main sections: (a) Methods used to assess the past and current BGI hydrologic variables; and, (b) Scheme of analysis to compute the future projections from these variables.

Experimental methodology for the assessment of past and present BGI hydrologic design variables

Daily and hourly precipitation data were examined to assess hydrologic design variables, comparing the differences between data intervals. Two 30-year overlapping periods (1974-2003 and 1991-2020) were utilized to establish Climatological Standard Normals for climatic analysis, following the recommendations of the WMO (2015). Furthermore, a more recent timeframe spanning from 2013 to 2022 was included to incorporate the assessment of the impact of the most recent period and the latest data. The WQ storm event considered the rainfall depths associated with capturing 85 to 90% of all rainfall volume, being calculated for this study as the 85-90th percentile storm depth of the record rainfall events and the 85-90% volume of annual rainfall that it has been widely set as the runoff volume to be captured by BGI techniques. Then, extreme distributions were considered to develop the IDF curves (Gumbel, Generalized Extreme Value –GEV–, and SQRT-ET max using the L-Moments). The goodness of fit between those distributions and the observed data was assessed through the Root Mean Square Error (RMSE) and the Chi-Square test. In addition, the coefficient of determination (R^2) and the Nash-Sutcliffe Efficiency coefficient (NSE) were used to carry out the regression validation. Moreover, Mann-Kendall analyses were performed to understand the long-term climatic trends in the precipitation patterns at the four locations in NC.

Computing future projections in BGI hydrologic design variables

Future climate projections were estimated for the main design variables (WQ storm event and IDF curves), using two representative concentration pathways (RCP) and 24-hour data intervals: (1) RCP 4.5 as an intermediate climate change scenario; and, (2) RCP 8.5 as the worst-case scenario. In addition, the synthetic design hyetographs were built using the IDF curve previously developed, which are commonly elaborated to develop further runoff simulations and to identify BGI hydrological performance failures. With this aim, the Multivariate Adaptive Constructed Method (MACA) was used as the regional downscaling process for daily precipitations with a 6 km resolution, containing the climate models (see Table 1) from the Coupled Model Inter-Comparison Project Phase (CMIP5) for observed historical data for the period 1950-2005; and, future projections for the period 2006-2099, based on the recommendations for the Southeast region using the U.S. Climate Resilience Toolkit.

Table 1. Coupled climatic methods (CMIP5) used in MACA to analyze future projections for precipitations.

bcc-csm1-1 (China)	bcc-csm1-1-m (China)	BNU-ESM (China)	CanESM2 (Canada)
CCSM4 (USA)	CNRM-CM5 (France)	CSIRO-Mk3-6-0 (Australia)	GFDL-ESM2G (USA)
GFDL-ESM2M (USA)	HadGEM2-CC365 (UK)	HadGEM2-ES365 (UK)	inmcm4 (Russia)
IPSL-CM5A-LR (France)	IPSL-CM5A-MR (France)	IPSL-CM5B-LR (France)	MIROC5 (Japan)
MIROC-ESM (Japan)	MIROC-ESM-CHEM (Japan)	MRI-CGCM3 (Japan)	NorESM1-M (Norway)

Case study

North Carolina has a long-standing tradition in designing and implementing BGI, including a stormwater manual providing the values for the design variables. An update (incorporating new rainfall variations) was needed for these data. Four locations were selected, representing differential Köppen-Geiger climatic classifications, covering the most relevant areas of the state: Asheville (Mountains-Western; Cfb), Charlotte (Piedmont-Central; Cfa), Raleigh-Durham (Piedmont-Eastern; Cfa), and Wilmington (Coastal Plains; Cfa). Data for all weather stations used in the study are provided below in Table 2.

Table 2. Weather stations' data at the four locations**.**

Weather station	ID	Latitude	Longitude	Altitude (m)	Annual rainfall (mm)	Daily data available since
Asheville	310300(1)	35.43194	-82.5375	645	1,184	1946
Charlotte Douglas	311690(1)	35.22361	-80.95528	222	1,077	1939
Raleigh-Durham	317069(1)	35.86667	-78.78333	133	1,094	1944
Wilmington	319457(1)	34.2675	-77.89972	10	1,331	1933

(1) Network: Cooperative. Data accessed through the Cardinal Data Retrieval System, North Carolina State Climate Office (NCSO).

Results and discussion

The results are divided into two main sections of interest, following up from the methodology section: (a) Results from the past and current values for the WQ storm event, showing the main impacts and implications in future design and research; and, (b) Results for the future projections estimated using coupled climate models, presenting the main impacts in the synthetic design hyetographs used for BGI modelling, providing insights into the effects for hydrologic performance and potential failure.

Past and present BGI hydrologic design variables – The WQ storm event

Storm events were isolated using a 6-hour inter-event period commonly utilized in the literature (Bean, 2005). Then, the volumetric and percentile methods were used to calculate the WQ storm for BGI design (Figure 1). The volumetric method appears to be more accurate in the case of NC as it uses the concept/abstraction of the captured runoff volume, which dilutes the impact of large events such as hurricanes or other cyclonic events. However, the percentile method, when used in sub-daily data, allows for an increase in the number of large events, which are usually part of the same extreme event. The result of this is to elevate the design storm value considerably.

Another outcome that is important to note is the fact that the use of daily data significantly underestimates the (WQ) storm depth, as it is less accurate to isolate storm events, which reassures and confirms previous findings from Bean (2005), who raises awareness about this issue for NC.
The values obtained, along with the calculated IDF curves, underscore the necessity for updating the hydrologic variables used in BGI design, as these variables directly influence the synthetic and real hyetographs used in modelling. As is clear in Figure 1, the most recent decade of observation yields (usually substantial) increases in the WQ event depth, being 1.5 times as much rainfall depth in the worst cases. As an aside, the Mann-Kendall test showed a significant change in precipitation patterns for the last 30-year period (1994-2023) (Z=2.2837, p=0.05), markedly increasing over the most recent 10 years, confirming climate change impacts for NC related to the WQ storm event.

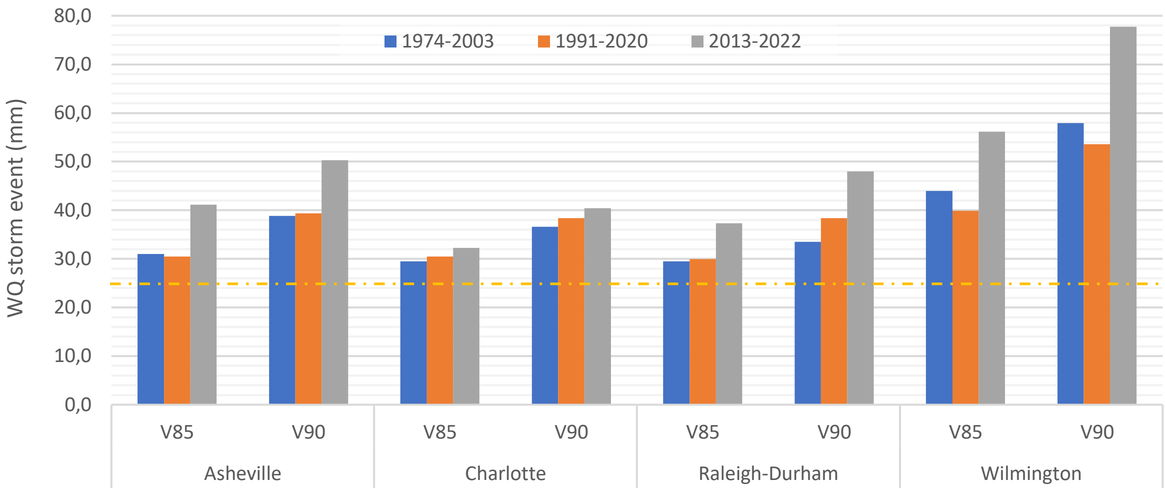

Figure 1. WQ storm (mm) for the V85 and V90 using the volumetric method fed by hourly precipitation data from the past and present periods for 8 jurisdictions. Asheville, Charlotte, Raleigh, and Wilmington are #'s 1, 3, 5, and 8, respectively.).

Figure 1 also illustrates the significant differences between climate areas in the state of NC, supporting the previous case to have different WQ storm events as described in the introduction. Another takeaway point from this research is the need to use sub-daily data. The V90 associated with the design standards in the state has been underestimated for the last past 3 decades, as it was usually calculated using daily data (25 mm for most of the state and 38 mm for the coastal areas), while sub-daily data reached 35-40 mm in most of the state and 58 mm in the coastal areas, for the same past periods of analysis. Then, results with daily data underestimate the values for the WQ storm event, as they are not able to compute high-intensity rainfall events within a 24-hour boundary, becoming a potential risk for practitioners designing BGI practices in the state of NC. This finding supports the previous research conducted by Bean (2005) and Mitchell (2024), who previously alerted about this particular issue. That was the main driver to show only the sub-daily data analysis in this paper, as depicted in Figure 1.
On the other hand, the increment registered in the WQ storm event for the last 10 years shows a worrying scenario where climate change affects the resilience of BGI practices by increasing the potential runoff conveyed to BGI practices for treatment and flooding mitigation, in line with the record-breaking rainfalls and floods registered in the state over the past decade.
These findings about the WQ storm event emphasized the need to revisit the design features and elements of BGI practices, especially those directly influenced by the WQ storm event such as the surface area occupied by the BGI and the storage depth. Therefore, it affects the need for more space in the urban environment and transportation infrastructures where BGI are commonly implemented, as well as the cross-section and how deep they need to reach in the ground to allow for sufficient storage capacity.

Future projections in BGI hydrologic design variables – The synthetic hyetographs for modelling

Future projections were analyzed using 24-hour data intervals beginning with the past and current period depicted in Figure 2, where observed data is compared with the results computed from the IPSL-CM5B-LR coupled climatic model (see Table 1). This model reported the best goodness-of-fit among the climate models listed in Table 1 (R^2 of 0.9512 and NSE of 0.8913).

Raleigh-Durham was selected to highlight the main analysis as it was chosen in the past as the area to develop the initial 25 mm (1 inch) WQ storm event using 24-hour data.

Figure 2 present 2 sets of columns indicating the value of the synthetic event in mm (blue), and the theoretical runoff computed using the curve number method - CN (orange), also provided in mm.

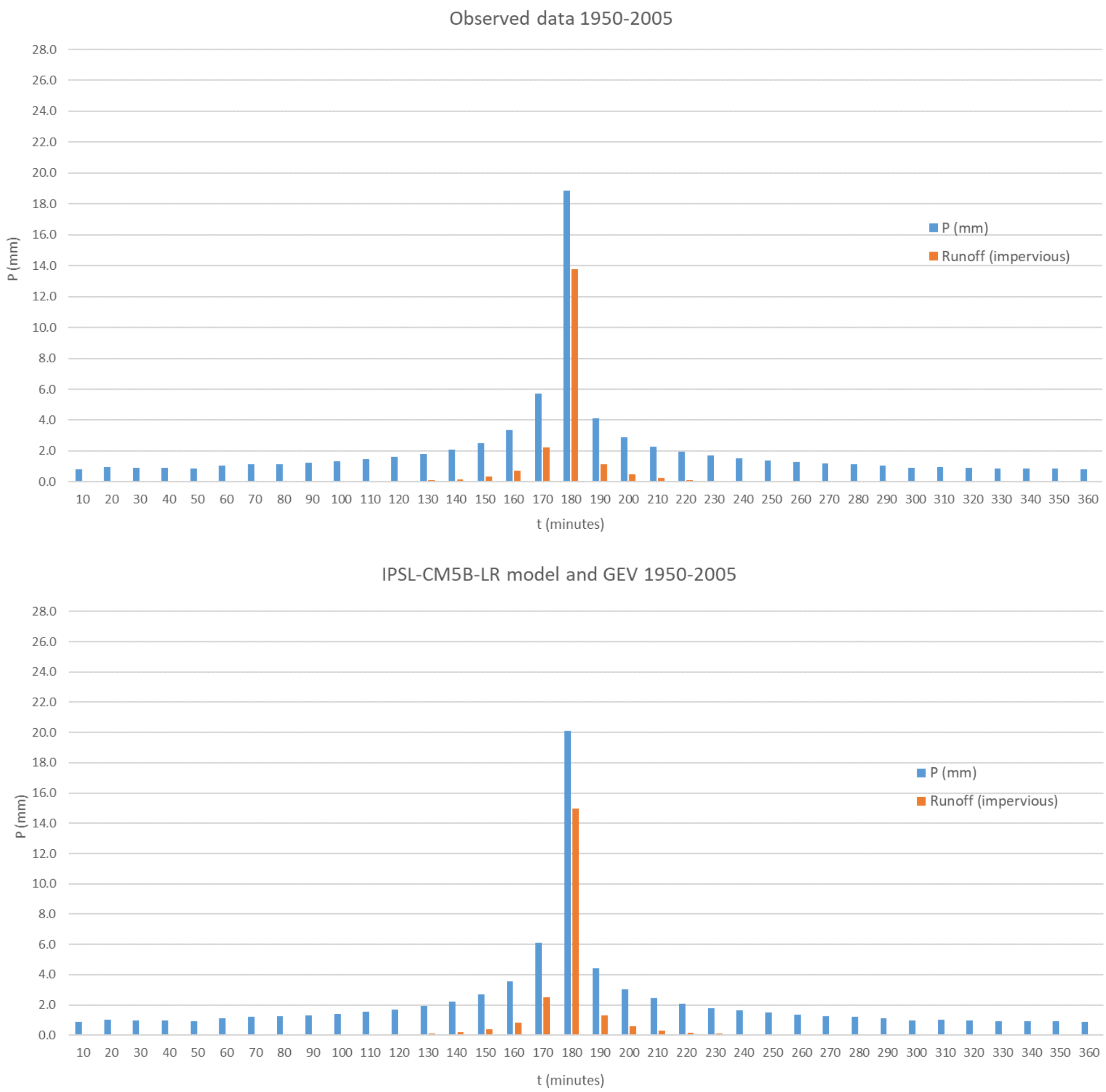

Figure 2. Synthetic design hyetographs obtained from the IDF curves for past and present (1950-2005), considering a T=100 years and t=6 hours in Raleigh-Durham, NC, USA.

The synthetic design hyetographs elaborated for modelling in the past and current scenarios for Raleigh-Durham (Figure 2) showed similar numbers when using the alternating block method, displaying a good fit between the observed real data and the climate model selected. This finding represents a good start for the future projections presented in Figure 3.

Then, future projections, computed using the IPSL-CM5B-LR coupled climatic model, indicate an increase in these design variables. That is illustrated by the synthetic hyetographs for Raleigh-Durham, which represent a 6-hour duration event with a 100-year return period (see Figure 3), commonly used in BGI practices of larger size and great capacity for flooding mitigation (these are the most likely affected practices given the new WQ storm events). These hyetographs were developed using IDF curves based on the GEV distribution, which demonstrated the best fit for the selected future climate model, presenting R^2 of 0.9902, NSE of 0.9867, and RMSE of 0.0131. Figure 3 also present 2 sets of columns under the same legend depicted in Figure 2, presenting the results for two RCPs (4.5 and 8.5).

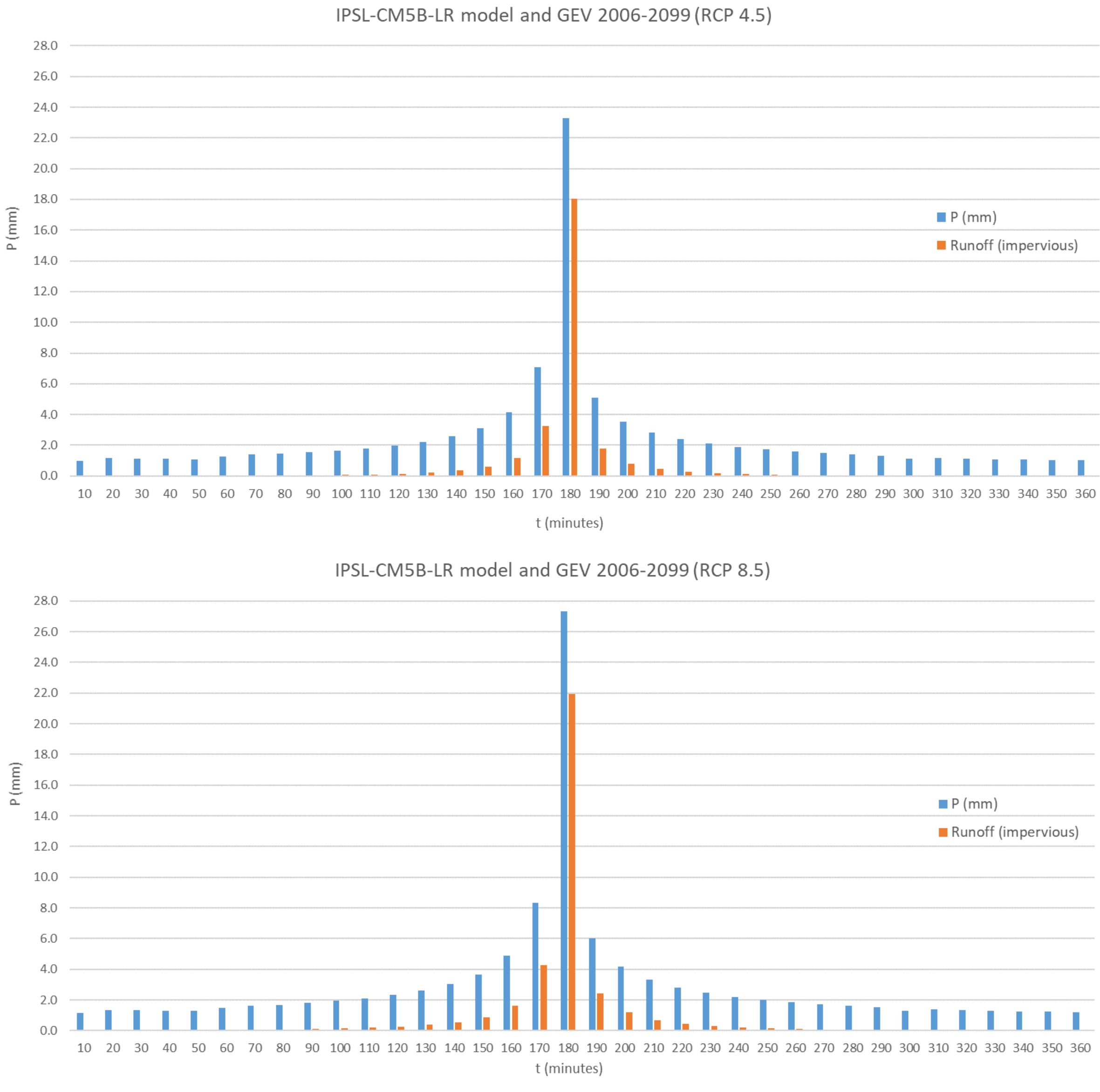

Figure 3. Synthetic design hyetographs obtained from the IDF curves for future projections (2006-2099) under different scenarios (RCP 4.5 and 8.5), considering a T=100 years and t=6 hours in Raleigh-Durham, NC, USA.

The increase in the synthetic hyetographs for RCPs 4.5 and 8.5 (Figure 3) is significant in comparison with the current and past scenarios (Figure 2). As a consequence, all simulations and modelling deriving from these results will impact, not only the peak flows associated with the WQ storm event, but also the BGI hydrologic and water quality treatment performances in the long-term. This hyetographs are some of the main inputs introduced in modelling programs such as the EPA's SWMM, and will allow the identification of potential elements of hydrologic failures and areas to be retrofitted and improved for climate resilience purposes.

Conclusions and future work

This study provides valuable initial insights and lessons for designers, policymakers and practitioners around the use of methods and data intervals in calculations for BGI design and modelling. The use of inaccurate data intervals to calculate the WQ storm event are already underestimating the value to be used in BGI design, posing a risk under varying climate change scenarios, which further increase these values. In addition, the method employed to compute the rainfall depth significantly influences the outcome, needing further research across the world under local conditions. Climate change has already impacted design variables in NC, setting the ground for more investigations, in line with Hathaway et al. (2024). Future work should be conducted to improve future projections, implementing the Localized Constructed Analogs (LOCA) based on CMIP6, as the statistical downscaling method for NC, as well as extending the scope of the study to the weather station network in the state.

Finally, BGI should be redefined from the planning and design stages with climate change resilience in mind, incorporating potential areas and elements for future retrofitting in order to adapt BGI practices to the effects and uncertain variability of climate change.

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References

Alamdari, N. and Hogue, T. S. (2022) Assessing the effects of climate change on urban watersheds: a review and call for future research. Environmental Reviews, 30(1), 61–71. https://doi.org/10.1139/er-2021-0003

Bean. E. (2005). A field study to evaluate permeable pavement surface infiltration rates, runoff quantity, runoff quality, and exfiltrate quality [North Carolina State University]. PhD thesis. [online] https://repository.lib.ncsu.edu/items/c837c72a-b432-42a5-98eb-11f4b49f8b9d

D’Ambrosio, R., Longobardi, A., and Schmalz, B. (2023) SuDS as a climate change adaptation strategy: Scenario-based analysis for an urban catchment in northern Italy. Urban Climate, 51. https://doi.org/10.1016/j.uclim.2023.101596

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J. L., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D., and Viklander, M. (2015) SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. Urban Water Journal, 12(7). https://doi-org.uniovi.idm.oclc.org/10.1080/1573062X.2014.916314

Hathaway, J. M., Bean, E. Z., Bernagros, J. T., et al. (2024). A Synthesis of Climate Change Impacts on Stormwater Management Systems: Designing for Resiliency and Future Challenges. Journal of Sustainable Water in the Built Environment, 10(2). https://doi.org/10.1061/jswbay.sweng-533

IPCC. (2022). Climate Change 2022 - Mitigation of Climate Change - Full Report. In Cambridge University Press (Issue 1).

Mitchell, C. E. (2024) Resilience of Stormwater Control Measures to Floods, Bioterrorism, and Industrial Runoff [North Carolina State University]. PhD thesis. [online] https://repository.lib.ncsu.edu/items/89709928-c451-4a4c-b491-d948b304f341

Nguyen, T.-H., & Nguyen, V.-T.-V. (2020). Linking climate change to urban storm drainage system design: An innovative approach to modelling of extreme rainfall processes over different spatial and temporal scales. Journal of Hydro-Environment Research, 29, 80–95. https://doi.org/10.1016/j.jher.2020.01.006

Nodine, T. G., Conley, G., Riihimaki, C. A., Holland, C., and Beck, N. G. (2024) Modelling the impact of future rainfall changes on the effectiveness of urban stormwater control measures. Scientific Reports, 14(1). https://doi.org/10.1038/s41598-024-53611-1

Zheng, J., Chen, X., Kawaike, K., et al. (2024). Response of urban flood resilience to climate change: An exploration with a novel performance-based metric considering the socioeconomic impacts of damage costs. Journal of Hydrology, 645(PB), 132260. https://doi.org/10.1016/j.jhydrol.2024.132260

World Meteorological Organization (2015). Abridged Final Report with Resolutions. Cg-17 Seventeenth World Meteorological Congress, Geneva. Session Report.