frontiers | Frontiers in Built Environment

TYPE Original Research
PUBLISHED 22 January 2026
DOI 10.3389/fbuil.2026.1731955

OPEN ACCESS

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RECEIVED 24 October 2025
REVISED 05 January 2026
ACCEPTED 07 January 2026
PUBLISHED 22 January 2026

CITATION
Chathuranika IM, Asante A, Borhani F, Wang X, Erten-Unal M and Ismael D (2026) Performance assessment and design improvements for an urban coastal detention basin under intensifying rainfall extremes.
Front. Built Environ. 12:1731955.
doi: 10.3389/fbuil.2026.1731955

Performance assessment and design improvements for an urban coastal detention basin under intensifying rainfall extremes

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Coastal urban areas are increasingly exposed to flooding driven by more frequent and intense rainfall events, rising sea levels, and expanding impervious surfaces. Norfolk, Virginia, a low-lying coastal city with aging stormwater infrastructure, faces heightened vulnerability to these hydrologic pressures. This study evaluates the hydraulic performance of an existing urban detention basin within the Edgewater–Larchmont catchment under 10-, 50-, and 100-year, 2-h design storms using the U.S. Environmental Protection Agency's Storm Water Management Model (SWMM). Simulations were conducted for both pre- and post-development conditions to assess changes in peak discharge, storage capacity, and water level dynamics. Results show that urbanization, which increased impervious area from 5% to 70%, substantially intensified runoff generation. Peak discharges increased from 1.44 m^3/s under pre-development 10-year conditions to 2.81 m^3/s and 3.51 m^3/s under post-development 50-year and 100-year storms, respectively, while total runoff volumes approximately doubled. Although total basin storage capacity was not exceeded, the detention basin became hydraulically limited during extreme storms as effective storage below the outlet elevation was rapidly exhausted, leading to elevated peak outflows. Outlet elevation adjustments that increased effective detention storage improved flow attenuation and reduced post-development peak discharges toward pre-development levels. This highlights the value of integrating hydrologic modeling with adaptive infrastructure design to enhance flood resilience and support evidence-based, climate-adaptive stormwater planning.

KEYWORDS

adaptive infrastructure design, detention basin, rainfall extremes, stormwater management, urban flood resilience

1 Introduction

Effective stormwater management is essential in urban and suburban planning to minimize the adverse impacts of surface runoff on public safety, infrastructure, and surrounding ecosystems. Rapid urbanization and the spread of impervious surfaces disrupt the natural hydrologic balance, leading to higher peak discharges, accelerated erosion, and degraded water quality in downstream (Mahmood et al., 2017; Walsh et al., 2005). Traditional drainage designs, which prioritize the rapid removal of stormwater from developed areas, have often worsened flooding and pollution problems in highly urbanized regions (Pereira Souza et al., 2019). Rethinking and modernizing stormwater management practices is therefore critical to achieving sustainable urban growth and enhancing resilience to flooding.

In recent decades, urban drainage design has increasingly integrated ecological, hydrological, and social dimensions to develop more sustainable and resilient systems (Riflan et al., 2022). Practices such as Low Impact Development (LID) and Green Stormwater Infrastructure (GSI) have gained prominence for improving runoff quality, adding aesthetic and recreational value, and preserving local ecosystems (Kourtis et al., 2018; Zanandrea and Silveira, 2018). The core principle of LID is to maintain pre-development state (Elliott and Trowsdale, 2007). Achieving this balance, however, remains challenging amid rapid urban growth and evolving climatic conditions (Chathuranika et al., 2023; Ismael et al., 2024; Ismael, 2024; Ismael and Shealy, 2024). Among the various Best Management Practices (BMPs), detention basins stand out as effective solutions for controlling stormwater runoff, mitigating flooding, and reducing pollutant loads. Their operational simplicity, cost-effectiveness, and proven reliability have made them fundamental components of modern stormwater management strategies (Salisbury and Obropta, 2016; Morsy et al., 2018; Abduljaleel et al., 2023).

Detention basins, often referred to as stormwater wet ponds, are engineered facilities designed to collect and temporarily retain stormwater runoff during rainfall events before releasing it gradually through a controlled outlet (Harrell and Ranjithan, 2003; Sadler et al., 2019). By regulating discharge rates, they help alleviate downstream flooding, reduce channel erosion, and enhance the overall hydrologic stability of watersheds. Their dual role in flood attenuation and water quality improvement has established detention basins as a cornerstone of sustainable stormwater management strategies worldwide. However, their reliability and resilience are increasingly challenged by climate change. CO_2-driven climate warming is projected to intensify both the frequency and magnitude of extreme precipitation events across the United States (Hoerling et al., 2016; Huang and Swain, 2022; Nodine et al., 2024). This trend poses serious concerns for infrastructure based on historical rainfall records rather than potential future variability (Markolf et al., 2021). Anticipated hydrologic impacts include larger runoff volumes, elevated peak flows, and increased risks of system overload or failure (Zahmatkesh et al., 2015). When combined with urban expansion, aging infrastructure, and limited maintenance, these effects amplify flooding, strain drainage systems, and degrade water quality (Grove et al., 2001; Tang et al., 2005; Zhao et al., 2019).

To address these challenges, hydrological and hydraulic modeling tools have become indispensable for evaluating and optimizing stormwater infrastructure. Among the commonly used platforms, such as DR3M–QUAL, HSPF, and STORM, the U.S. EPA SWMM remains one of the most versatile and widely adopted for simulating urban runoff quantity and quality (Rossman, 2010; USEPA, 1999). The SWMM framework enables detailed analysis of drainage networks, detention structures, and LID practices, making it a versatile tool for evaluating stormwater management strategies. When properly calibrated, it demonstrates strong predictive capability for observed hydrological responses (Agyare et al., 2017), making it valuable for urban flood mitigation and drainage design (Tsuji et al., 2019).

Norfolk, Virginia, presents an ideal setting for evaluating the resilience of stormwater detention systems under varying rainfall extremes. Its coastal position, low-lying terrain, and frequent exposure to intense rainfall, hurricanes, and the effects of sea-level rise create persistent challenges for effective stormwater management. Within this context, detention basins serve as key components of the city's flood-mitigation strategy by temporarily storing excess runoff and releasing it in a controlled manner, thereby reducing downstream flooding, erosion, and degradation of water quality (Harrell and Ranjithan, 2003). The combination of high-intensity rainfall, extensive impervious surfaces, and coastal vulnerability in Norfolk highlights the importance of designing detention systems capable of maintaining reliable performance under changing hydrologic conditions.

This study evaluates the performance and resilience of an existing detention basin located within the Edgewater–Larchmont–James Crescent Catchment in Norfolk, Virginia, under both pre-development and post-development conditions across a range of rainfall scenarios. Using the EPA SWMM modeling platform, the research integrates field observations and hydrological simulations to analyze runoff dynamics, storage capacity, and peak flow attenuation. Through an assessment of design optimization, hydraulic efficiency, and adaptive behavior, the study provides insights into how detention basins can be effectively planned and managed to strengthen the resilience of urban stormwater systems under variable rainfall extremes. The analysis evaluates detention basin performance using 2-h design storms for multiple return periods, focusing on how increasing rainfall magnitude affects storage behavior and peak discharge. Finally, the study identifies an optimal pond size and outlet configuration that maintain consistent performance across multiple rainfall scenarios, providing guidance for developing more robust and resilient stormwater systems in coastal urban environments such as Norfolk.

2 Materials and methods

2.1 Study area

The study was conducted in the Edgewater and Larchmont neighborhoods of Norfolk, Virginia, United States. Norfolk located in southeastern Virginia, experiences a humid subtropical climate, characterized by hot, humid summers and mild winters (Chathuranika and Ismael, 2025a). The city receives an average annual precipitation of approximately 1,143 mm, distributed relatively evenly throughout the year. However, summer months tend to be slightly wetter due to frequent thunderstorms and the influence of tropical-origin weather systems such as hurricanes and tropical storms. During the warmest months, particularly July and August, daytime temperatures often exceed 24 °C, with occasional heatwaves reaching 27 °C. High humidity levels during this period intensify thermal discomfort. Winters are generally mild, with average daytime temperatures ranging between 4 °C and 10 °C

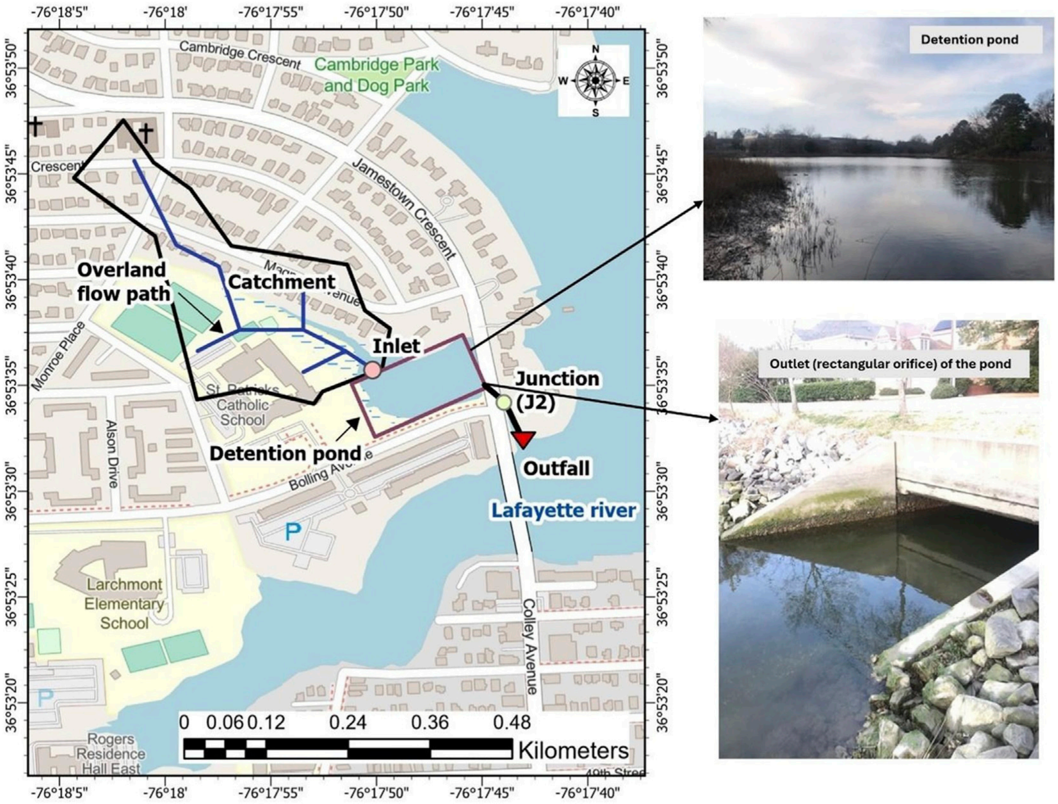

FIGURE 1
Selected detention basin and its contributing catchment area (James Crescent) used in this study, showing images of the pond and the rectangular orifice at its outlet.

from December through February. Snowfall is infrequent and typically short-lived due to the region's moderate winter temperatures.

The topography of the study area is generally low-lying, typical of coastal regions in Norfolk (Chathuranika and Ismael, 2025b). Elevations across Larchmont vary only slightly, creating a predominantly flat landscape. The highest elevations are near streets adjacent to the Lafayette River, but these variations are minimal. Due to its low elevation and proximity to tidal waterways, the area is highly susceptible to flooding during heavy rainfall and storm surges associated with hurricanes and tropical storms. To mitigate flood risks, the neighborhoods rely on an integrated stormwater management network that includes storm drains, conduits, and detention ponds designed to control runoff and reduce property inundation.

One such detention basin, located in the Larchmont neighborhood, serves as a key element of the local stormwater management system (Figure 1). The pond occupies a landscaped setting with grassy embankments and mature trees along its perimeter. It has a relatively large surface area that enables temporary storage of excess stormwater during intense rainfall events before releasing it at a controlled rate. The contributing catchment covers approximately 0.06 Km^2 (14.8 acres), with an average width of 393 m (1,289 ft) and a gentle surface slope of 0.03%. The surrounding area primarily consists of single-family residential properties, many constructed in the early 20th century, reflecting the established urban fabric of the community.

Hydrologically, the detention basin captures runoff from the catchment and conveys it through a rectangular orifice located at the outlet. The released flow passes through a junction, merges into an open rectangular channel, and ultimately discharges into the Lafayette River (Figure 1). This configuration allows for effective attenuation of peak flows while minimizing downstream flooding and erosion.

2.2 Data collection

Data collection integrated multiple sources and methods to characterize the hydraulic and physical properties of the detention pond, its catchment, and associated structures, including the rectangular orifice and open rectangular channel. The dimensions and geometry of the detention pond were determined using Google Earth Pro and ArcGIS Pro, which were also used to delineate the catchment boundary and extract key physiographic parameters. Catchment characteristics such as area, slope, elevation, and overland flow paths were derived through spatial analysis in ArcGIS Pro, providing a detailed understanding of the hydrologic behavior within the study area.

Field surveys were conducted to obtain the geometric and hydraulic properties of the rectangular orifice and open channel,

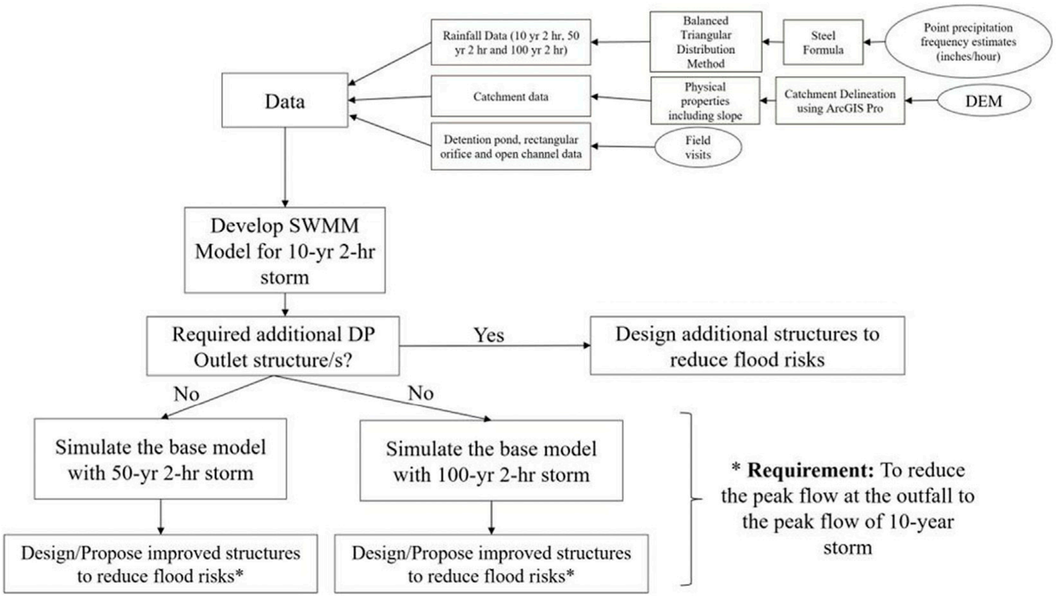

FIGURE 2
Overall methodology for the study.

enabling direct observation and precise measurement of structural dimensions under existing conditions. Point precipitation frequency data for Norfolk, were sourced from the National Oceanic and Atmospheric Administration (NOAA) through the Precipitation Frequency Data Server (https://hdsc.nws.noaa.gov/). Additionally, Digital Elevation Model (DEM) data were acquired from NASA's Earthdata Search platform (https://www.earthdata.nasa.gov/), providing essential terrain information for topographic analysis and catchment modeling.

2.3 Methodology

This study employed the U.S. EPA SWMM 5.0 to simulate rainfall–runoff processes and evaluate the hydraulic performance of an existing detention basin in mitigating flood risks within the Larchmont catchment, Norfolk, Virginia. The modeling approach was designed to assess the effectiveness of detention-based LID and BMPs under different rainfall conditions. To establish a baseline for comparison, the pre-development scenario was simulated by assigning natural catchment characteristics, most notably a low impervious coverage of 5% and applying infiltration, surface roughness, and storage parameters representative of undeveloped land conditions. Imperviousness values of 5% (pre-development) and 70% (post-development) were determined through visual interpretation of land cover using Google Earth Pro, and were used as scenario-based representations of undeveloped and urbanized conditions within the catchment. In this study, the 10-year, 2-h pre-development storm was used as the baseline because it reflects the natural hydrologic response of the catchment prior to substantial urbanization. The overall methodological framework, integrating data collection, model development, and simulation analysis, is presented in Figure 2, while Figure 5 illustrates the schematic configuration of the stormwater model.

The analysis began with preparing input data, including rainfall characteristics, catchment parameters, and hydraulic properties of the detention pond, rectangular orifice, and open rectangular channel. Catchment delineation and characterization were carried out in ArcGIS Pro using Digital Elevation Model (DEM) data and field observations to determine key physical features such as area, slope, and overland flow paths. The resulting spatial data were incorporated into EPA SWMM to establish a baseline hydrologic model representing the 10-year, 2-h storm.

The model setup consisted of one subcatchment, a detention pond, a rectangular orifice, an open rectangular channel, one junction, and an outfall. Runoff generated from the subcatchment was directed into the detention pond for temporary storage and controlled release. The simplified SWMM configuration used in this study, including a single subcatchment representation and an idealized drainage network was intended to support controlled scenario testing rather than to produce fully calibrated quantitative predictions. The Horton infiltration method was applied to represent infiltration losses, while dynamic wave routing simulated unsteady hydraulic flow conditions. Model parameters for pre-development and post-development conditions are summarized in Tables 1–3.

2.3.1 Design of storms

Rainfall data served as a critical input for stormwater modeling and design (Riflan et al., 2022). In this study, point precipitation frequency estimates (mm/hr) for Norfolk, Virginia, were obtained from NOAA's Precipitation Frequency Data Server. A 2-h storm duration was selected because short, high-intensity rainfall events typically govern runoff generation in small urban catchments, where extensive impervious surfaces and short flow paths produce a rapid hydrologic response. Using the Steel formula, site-specific frequency-related coefficients (a, b, and c) were determined

TABLE 1 Properties for sub-catchment for three different development scenarios (% Imperv: Impervious area percentage, N-Imperv: Manning coefficient for impervious surfaces, N-Perv: Manning coefficient for pervious surfaces, Dstore-Imperv: Depression storage of impervious area, Dstore-Perv: Depression storage of pervious area, and %Zero-Imperv: Zero storage impervious area percentage).

Parameter	Pre-development (grassland)	Post-development (with DP)	Post-development (without DP)	Source
% Imperv	5	70	70	Google Earth Pro
N-Imperv	0.03	0.03	0.03	Expert opinion
N-Perv	0.05	0.05	0.05	Expert opinion
Dstore-Imperv	1	0.25	0.25	Expert opinion
Dstore-Perv	1	1	1	Expert opinion
%Zero-imperv	25	25	25	Expert opinion
Subarea routing	OUTLET	OUTLET	OUTLET	
Percent routed	100	100	100	
Infiltration data	Horton	Horton	Horton	

TABLE 2 Parameters for infiltration model (Horton).

Parameter	Value	Source
Maximum infiltration rate	14.3 mm/h	SWMM Reference Documentation (2024); Expert opinion
Minimum infiltration rate	5.08 mm/h	SWMM Reference Documentation (2024); Expert opinion
Decay constant	6.5	SWMM Reference Documentation (2024); Expert opinion
Drying time	7 h	SWMM Reference Documentation (2024); Expert opinion
Maximum volume	0	

TABLE 3 Properties of closed rectangular orifice and rectangular open channel.

Property	Orifice 1	Open channel	Source
Inlet node	Detention pond	J2	
Outlet node	J2	Outfall	
Shape	Closed rectangular	Rectangular open	
Type	Side		
Height (m)	1.27	3.0 m	Field observations
Width (m)	3.81		Field observations
Length (m)		55.71 m	Google Earth Pro
Roughness		0.03	
Initial/Inlet offset (m)	0.30	0	
Outlet offset		0	
Entry loss coefficient		0.3	Expert opinion
Exit loss coefficient		1	Expert opinion
Discharge coefficient	5.22		Expert opinion

for the 10-year, 50-year, and 100-year, 2-h design storms, as shown in Equation 1:

$$i = \frac{a}{(t + b)^{c}} \tag{1}$$

where i represents rainfall intensity and t denotes storm duration.

These coefficients were used to generate design storms through the balanced triangular distribution method, producing synthetic hyetographs that represent realistic rainfall patterns for each return period. An areal adjustment factor of 0.999 was applied to account for spatial variability within the catchment. The resulting rainfall inputs were then used in SWMM simulations to evaluate the detention pond's hydraulic response under different rainfall intensities and durations.

The 10-year storm produced a total rainfall depth of 160.53 mm with a maximum intensity of 400.05 mm/h. The 50-year storm exhibited a total rainfall of 226.31 mm and a peak intensity of 496.82 mm/h, reflecting a substantial increase in precipitation magnitude. The most extreme event, the 100-year storm, recorded a total rainfall of 259.08 mm over the same period, with a maximum intensity of 535.94 mm/h (Figure 3). This highlights the pronounced variability in rainfall intensity and volume across different storm return periods. The findings highlight the critical importance of implementing resilient stormwater management systems capable of accommodating extreme precipitation events to minimize flood risks and protect downstream infrastructure.

2.3.2 Detention pond design scenarios

The modeling framework in EPA SWMM followed a systematic approach to assess the detention pond's performance under multiple storm scenarios. A base model was first developed for the 10-year,

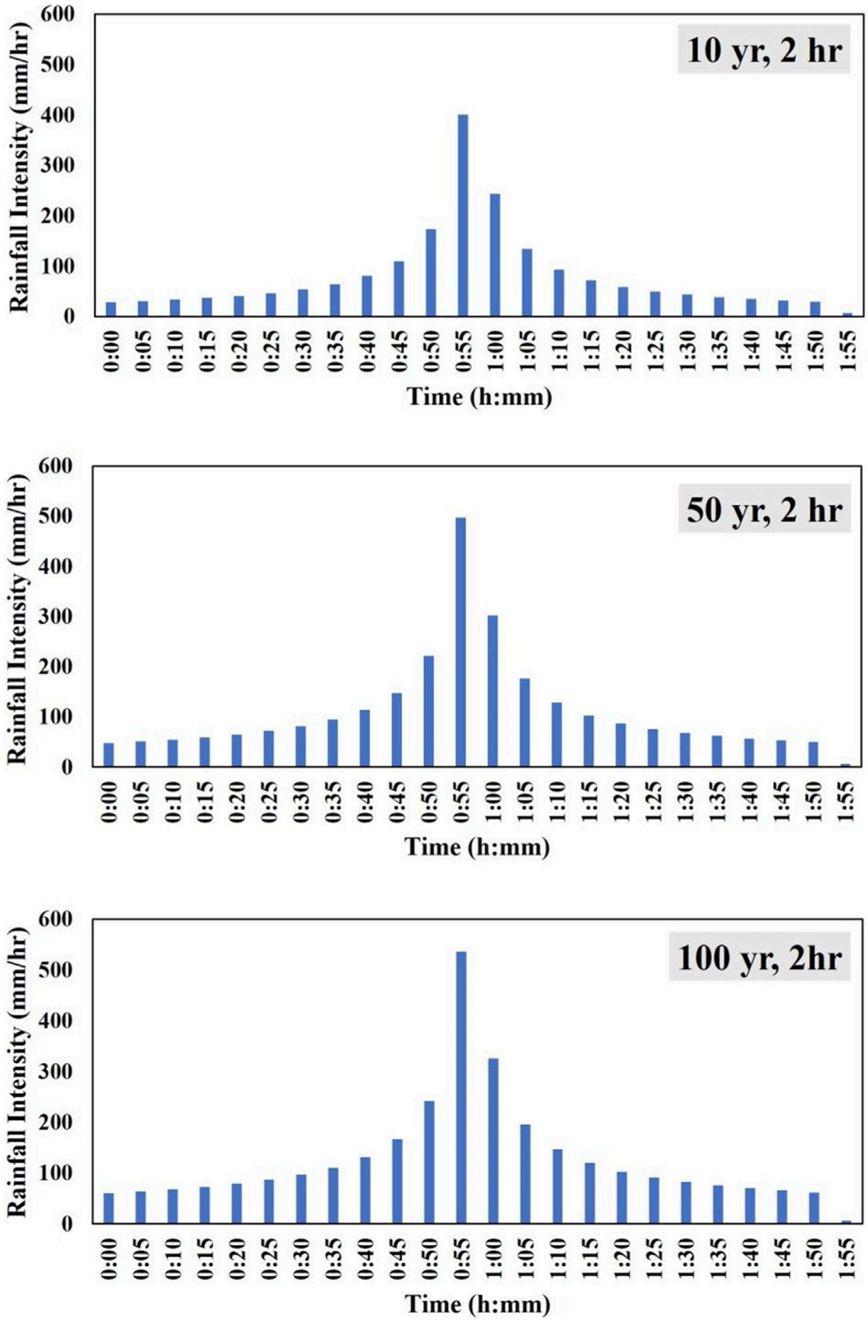

FIGURE 3
Rainfall intensity–time distributions for the 10-year, 50-year, and 100-year, 2-h design storms, illustrating the temporal variation in rainfall intensity for each storm magnitude.

2-h design storm (Figure 4), representing the benchmark event commonly used for stormwater infrastructure design in Norfolk, Virginia. The modeled maximum storage capacity of the detention pond is approximately 17,200 m^3, with a maximum allowable water depth of 1.40 m.

To evaluate system resilience under more severe rainfall, the model was used to simulate 50-year and 100-year, 2-h storms. Although the simulated pond storage and water depth during these events did not exceed the total geometric capacity of 17,200 m^3 or the maximum depth of 1.40 m, the effective detention volume below the outlet elevation was rapidly exhausted. This resulted in early and elevated outflows that substantially exceeded the 10-year, 2-h pre-development peak discharge, indicating that the basin is hydraulically limited from a flow-control perspective rather than by total storage capacity. To address this limitation, design modifications were evaluated that focused on increasing effective detention storage by adjusting the rectangular orifice inlet offset, thereby delaying the onset of discharge and reducing post-development outflow rates toward the 10-year, 2-h pre-development condition. Figure 5 shows the

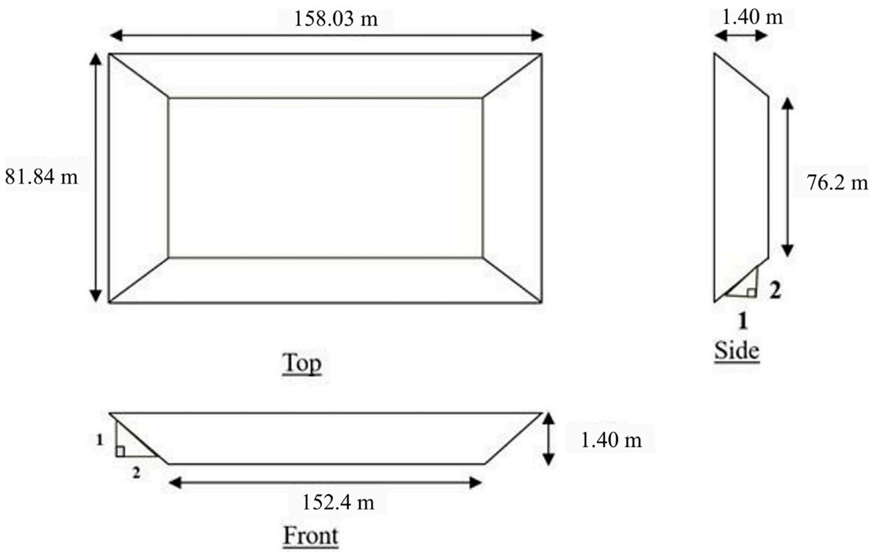

FIGURE 4
Detention pond layout used for the base model (10-year, 2-h storm) and for the 50-year and 100-year, 2-h storm simulations.

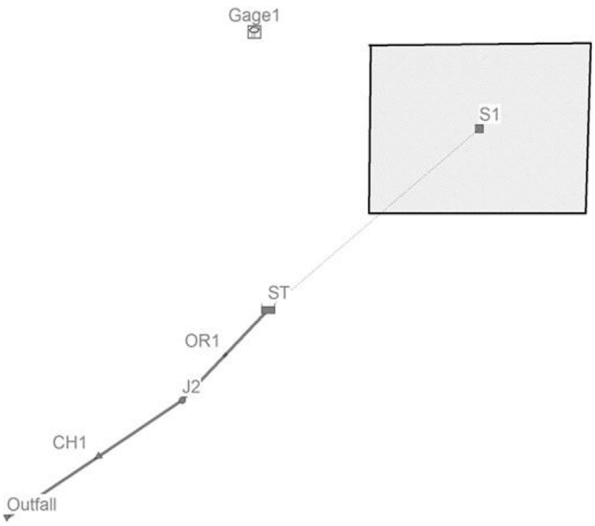

FIGURE 5
Layout of the SWMM model configuration used for the 10-year, 50-year, and 100-year, 2-h storm simulations, illustrating the subcatchment, detention pond, outlet orifice, open-channel reach, junction, and outfall included in each scenario.

site layout corresponding to all storm scenarios. Simulation results showed that higher-intensity storms rapidly consumed effective detention storage below the outlet elevation, resulting in elevated outflows and indicating limited peak-flow control under extreme rainfall conditions.

Flooding severity in this study was evaluated based on whether simulated pond water levels approached the limit of effective detention storage below the outlet elevation and whether downstream hydraulic structures operated near their maximum modeled flow depths. Under smaller storms, the basin retained runoff below the outlet elevation and regulated discharge effectively, indicating no surface flooding or hydraulic exceedance. In contrast, during the 50-year and 100-year events, effective detention storage was rapidly utilized, resulting in earlier and higher outflows, while downstream structures approached full-flow conditions. This behavior indicates elevated hydraulic stress and reduced peak-flow control under extreme rainfall conditions, even though the total basin storage capacity was not exceeded. Based on these findings, design modifications were developed to optimize pond performance. The proposed improvements focused on increasing storage capacity and enhancing outlet control efficiency to better regulate discharge rates and reduce downstream flooding. These scenarios were tested through iterative SWMM simulations to determine their effectiveness in attenuating peak flows, lowering runoff volumes, and improving system resilience under varying rainfall extremes.

The final objective was to ensure that the peak flow at the pond outfall during extreme storm events was reduced to a level comparable to or below that of the 10-year pre-development condition. Achieving this target demonstrates enhanced flood mitigation and supports the development of adaptive stormwater management strategies for coastal urban environments.

3 Results

3.1 Pre-vs. post-development hydrologic response

The hydrologic response of the Larchmont catchment differed substantially between pre- and post-development conditions. Under pre-development conditions, represented by the 10-year, 2-h pre-development storm, low impervious cover (5%) resulted in lower runoff volumes, attenuated peak flows, and longer times to peak across all simulated storm events. In contrast, post-development

TABLE 4 Comparison of runoff for pre- and post-development under 10-year, 50-year and 100-year, 2-h storms.

Design storm	Total rainfall (mm)	Runoff volume (mm)		Runoff coeff. (%)		Peak runoff (m^3/s)	
		Pre	Post	Pre	Post	Pre	Post
10-year	162.31	98.30	138.94	60.5	86.6	1.44	3.16
50-year	226.31	160.53	204.82	71.0	90.3	2.51	4.49
100-year	259.08	192.89	236.98	74.5	91.5	3.05	5.04

conditions, evaluated using the 50-year and 100-year, 2-h post-development storms, with impervious cover increasing to 70%, produced more rapid runoff generation, sharper hydrograph peaks, and significantly higher discharge rates.

As summarized in Table 4, peak discharge increased substantially under post-development conditions, nearly doubling for the 50-year, 2-h post-development storm and increasing by more than a factor of two for the 100-year, 2-h post-development storm, relative to the 10-year, 2-h pre-development condition. The reduced infiltration capacity and shortened runoff lag time associated with increased imperviousness highlight the dominant influence of urbanization on catchment-scale hydrologic response.

3.2 Comparison of the base model under 50-year, 2-h storm conditions

Under the 10-year, 2-h pre-development storm, the detention basin effectively regulated runoff and maintained controlled outflows, indicating adequate performance for moderate events. The post-development phase of the Larchmont catchment represents the hydrologic condition after urbanization, where impervious surfaces such as roads, rooftops, and other infrastructure significantly alter natural infiltration and runoff patterns. Following the hydrologic comparison in Section 3.1, the existing detention basin was found to be effective in mitigating localized flooding and managing stormwater runoff under the 10-year, 2-h pre-development baseline condition. To further evaluate its hydraulic performance under more extreme conditions, the EPA SWMM 5.0 model was used to simulate the system's response to a 50-year, 2-h post-development design storm.

Figure 6 presents outlet hydrographs showing total inflow to the outfall under both the 10-year, 2-h pre-development and 50-year, 2-h post-development conditions. The results indicate that the peak discharge for the 50-year, 2-h post-development storm ($Q = 2.81\ m^3/s$) was nearly twice that observed under the 10-year, 2-h pre-development scenario ($Q = 1.44\ m^3/s$). The time to peak was 1 h and 19 min for the 50-year, 2-h post-development event and 1 h and 30 min for the 10-year, 2-h pre-development event, demonstrating a slightly earlier and sharper peak under post-development conditions. Such elevated peak discharges can intensify erosion, downstream flooding, and streambank instability, posing risks to both the detention pond and the downstream hydraulic network.

As shown in Figure 7, the stored volume within the detention pond increased significantly during the 50-year, 2-h post-development storm compared to the 10-year, 2-h pre-development condition. While the pond effectively captured and temporarily retained runoff during smaller events, the larger inflow volumes associated with the 50-year, 2-h post-development storm rapidly utilized the effective detention volume available below the outlet elevation. A similar pattern was observed in the water depth variation within the pond (Figure 8), where greater ponding depths during the 50-year, 2-h post-development event reflected higher runoff volumes relative to the 10-year, 2-h pre-development condition; however, the rapid rise and subsequent drainage through the outlet structure limited the time available for infiltration during this event.

The hydrograph pattern under post-development conditions mirrors the timing of peak rainfall, with a pronounced and rapid rise in discharge followed by a quicker recession once rainfall ceased. This sharper response is primarily attributed to the substantial increase in impervious surface area, which rose from 5% under pre-development conditions to 70% under post-development conditions (Table 4). The reduced infiltration capacity and shorter lag time between rainfall and runoff generation contribute to higher and more abrupt flow peaks.

These findings demonstrate that, while the existing detention pond performs adequately under the 10-year, 2-h pre-development baseline, its ability to regulate peak flows becomes limited under the 50-year, 2-h post-development storm. Therefore, optimizing outlet control and effective detention storage is necessary to enhance flow regulation, minimize downstream impacts, and improve flood resilience under post-development conditions.

3.3 Comparison of the base model under 100-year, 2-h storm conditions

The EPA SWMM 5.0 model was further employed to simulate the system's response to a 100-year, 2-h post-development design storm in order to evaluate the detention pond's performance under extreme rainfall conditions. Figure 6 presents the outlet hydrographs comparing the 10-year, 2-h pre-development condition and the 100-year, 2-h post-development condition. The results indicate that the peak discharge during the 100-year, 2-h post-development storm ($Q = 3.51\ m^3/s$) was approximately 2.5 times greater than that recorded under the 10-year, 2-h pre-development storm ($Q = 1.44\ m^3/s$). The time to peak occurred at 1 h and 16 min for the 100-year, 2-h post-development event and 1 h and 30 min for the 10-year, 2-h pre-development event, reflecting a sharper and earlier peak under post-development extreme rainfall conditions.

Flooding within the catchment was characterized by simulated water levels within the detention pond and connected open-channel and outlet structures approaching their effective hydraulic limits. During the 100-year, 2-h post-development event, pond water levels remained elevated for an extended duration, and flow depths in

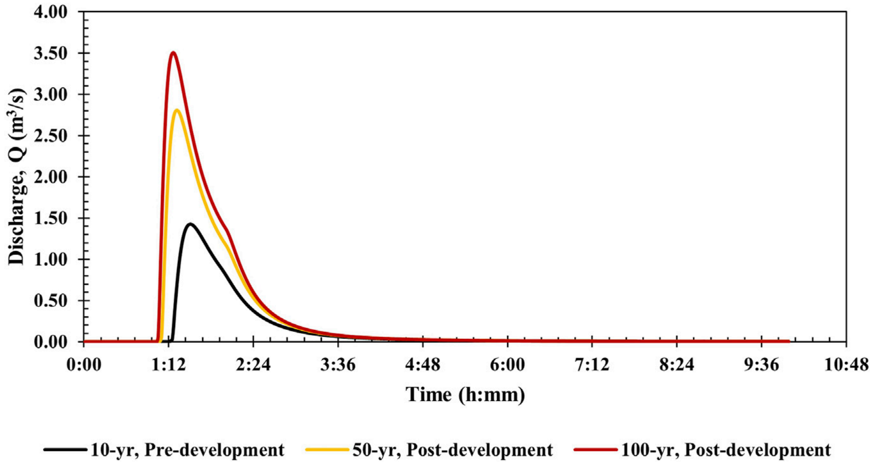

FIGURE 6
Outlet hydrographs for the 10-year, 2-h pre-development, 50-year, 2-h post-development, and 100-year storm simulations.

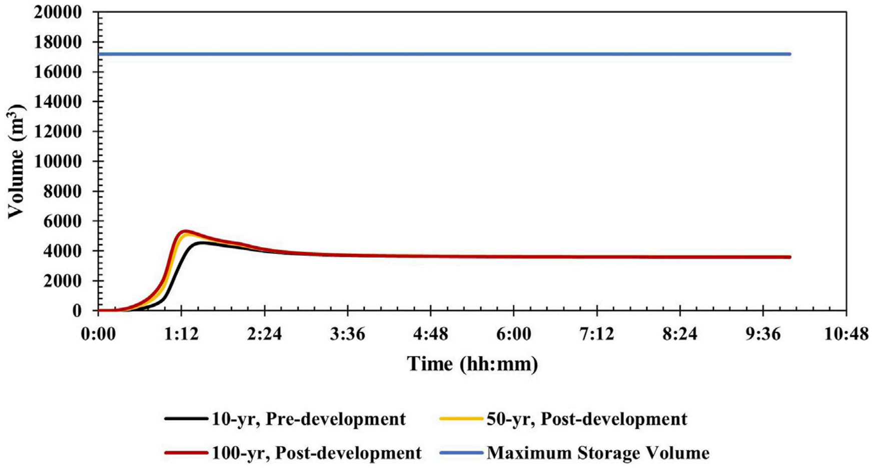

FIGURE 7
Variations of pond storage volume for the 10-year, 2-h pre-development, 50-year, 2-h post-development, and 100-year simulations.

downstream hydraulic structures approached modeled full-flow conditions, indicating substantial hydraulic loading and limited remaining conveyance capacity relative to the 10-year, 2-h pre-development baseline.

As illustrated in Figure 7, the detention pond stored a substantially larger volume of water during the 100-year, 2-h post-development event compared to the 10-year, 2-h pre-development storm. While the pond was able to temporarily retain a portion of the increased runoff, the effective detention storage available below the outlet elevation was rapidly utilized as inflow rates increased beyond those observed under pre-development conditions. This led to elevated pond water levels for prolonged durations, as shown in Figure 8. The higher runoff generated from the catchment required the pond to regulate significantly larger inflow volumes to attenuate peak discharges. When compared across design storms, peak runoff during the 100-year, 2-h post-development event was approximately 2.4 times greater than that of the 10-year, 2-h pre-development storm (Table 4), illustrating the nonlinear increase in runoff response with increasing storm magnitude.

Figure 8 shows variations in water depth within the detention pond under both storm events. During the 10-year, 2-h pre-development storm, water depth increased moderately and returned to normal levels within a relatively short duration, reflecting adequate performance for frequent, moderate-intensity events. However, under the 100-year, 2-h post-development storm, water depth rose sharply and remained elevated for a prolonged period, indicating substantial utilization of available detention storage and limited drainage recovery relative to the pre-development baseline. This prolonged high-water condition corresponds to the high-intensity runoff associated with rare, extreme rainfall events.

The 100-year, 2-h post-development storm simulation also indicated more widespread hydraulic stress within the catchment

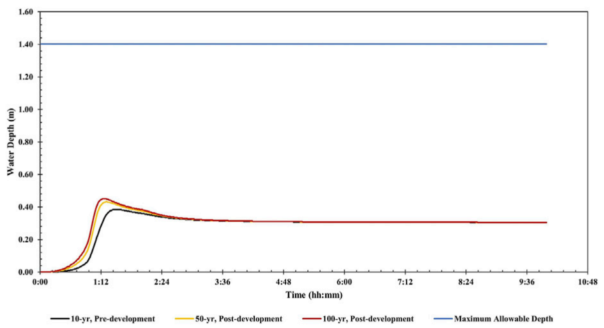

FIGURE 8
Variations of pond water level for the 10-year, 2-h pre-development, 50-year, 2-h post-development, and 100-year simulations.

relative to the 10-year, 2-h pre-development condition, affecting larger surface areas and placing increased demand on drainage infrastructure such as pipes, culverts, and outfalls. Many of these systems approached their modeled design capacities, increasing the potential for localized inundation and infrastructure stress under extreme rainfall.

These results demonstrate that, while the detention pond performs adequately under the 10-year, 2-h pre-development baseline, its ability to regulate peak flows becomes limited under the 100-year, 2-h post-development storm as effective detention storage below the outlet elevation is rapidly exhausted. This highlights the importance of explicitly accounting for extreme rainfall events when evaluating detention basin performance and developing adaptive stormwater management strategies for urban flood resilience.

3.4 Proposed modification to the pond design for 50-year and 100-year simulations

Results from the previous analyses revealed that post-development peak discharges for the 50-year and 100-year storms were approximately two to three times greater than those observed under the 10-year, 2-h pre-development condition. This substantial increase in flow magnitude indicates that, relative to the 10-year pre-development baseline, the existing detention pond has limited ability to regulate peak flows under extreme post-development storm events. Consequently, modifications to the pond design were evaluated to enhance flood mitigation performance and improve downstream flow regulation under 50-year and 100-year post-development conditions.

The first design modification focused on increasing effective detention storage to better accommodate the larger runoff volumes generated during 50-year and 100-year post-development storms. Increasing effective storage allows additional stormwater to be temporarily detained below the outlet elevation, thereby reducing peak discharge toward the 10-year pre-development target condition (Figure 9). In addition, adjustments to the inlet offset of the outlet control structure, specifically the rectangular orifice, were evaluated to achieve a more gradual and controlled release of water. Optimizing the inlet offset delays the onset of discharge and helps maintain outflow rates closer to those observed under the 10-year, 2-h pre-development scenario, reducing the potential for downstream flooding and erosion.

Simulation results demonstrated that the proposed design modifications significantly improved detention basin performance under both the 50-year and 100-year post-development storm conditions. The modified system effectively attenuated peak flows, bringing post-development discharge rates closer to those observed under the 10-year, 2-h pre-development condition. By temporarily storing excess runoff and releasing it at a controlled rate, the enhanced design reduced downstream hydraulic stress and improved overall system stability. The resulting variations in storage volume and water depth for the modified design are illustrated in Figures 10, 11, respectively.

Despite the improved hydraulic performance, opportunities for further enhancement of the detention pond are constrained by site-specific limitations. The study area has restricted available land, proximity to roads, underground utilities, and residential properties, and multiple property ownerships that limit the feasibility of expanding pond footprint or adding auxiliary storage facilities.

The proposed design modifications centered on optimizing the inlet offset of the rectangular orifice and thereby increasing the effective detention storage available below the outlet elevation, while maintaining the same total pond geometry successfully enhanced the pond's ability to regulate peak flows under 50-year and 100-year post-development storm events (Figure 12). The modified configurations increased total detention storage from approximately 17,200 m^3 under the 10-year pre-development condition to 44,400 m^3 and 55,800 m^3 for the adapted 50-year and 100-year post-development scenarios, respectively. Outlet control efficiency was improved by raising the inlet offset (the vertical distance between the pond bottom and the orifice invert), which delayed discharge initiation and increased temporary storage prior to release. These measures were selected to meet the 10-year pre-development peak-flow target within the constraints of a densely developed residential setting. Table 5 summarizes the baseline and modified design parameters and the corresponding hydraulic improvements. However, any future implementation must balance hydraulic performance gains with spatial, infrastructural, and administrative constraints within the Edgewater–Larchmont–James Crescent catchment.

4 Discussion

The results of this study highlight the significant influence of urbanization and rainfall variability on the hydraulic performance of detention-based stormwater systems within low-lying coastal environments such as Norfolk, Virginia. The modelling framework developed in EPA SWMM effectively demonstrated how land-use change, coupled with increased rainfall intensity, can substantially alter hydrological response and storage performance within small urban catchments. By integrating field-derived geometric parameters with synthetic rainfall distributions, this study provides a replicable modelling approach for evaluating detention basin resilience under evolving hydrologic conditions.

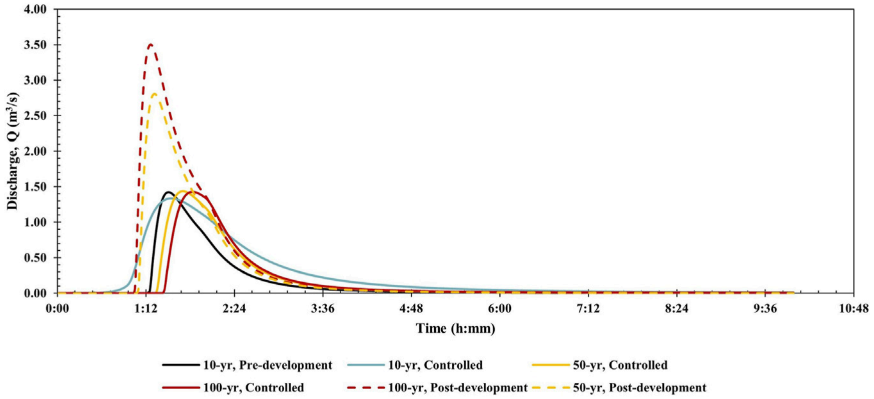

FIGURE 9
Controlled peak discharge for all the design storms.

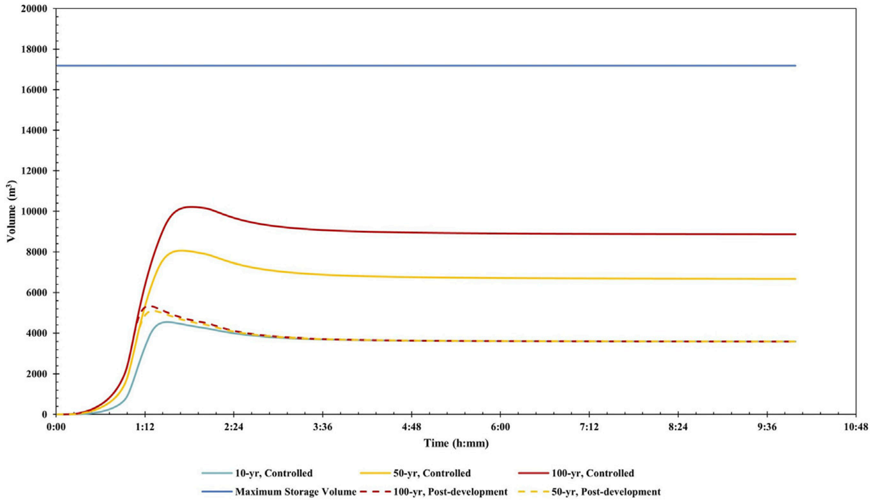

FIGURE 10
Variations in storage volume for the modified detention pond under 50-year and 100-year post-development storms.

4.1 Hydrologic response under urbanization

The comparison between pre-development and post-development conditions clearly indicates that urbanization substantially increases both runoff volume and peak discharge, consistent with findings from previous studies (Yang et al., 2025; Xu et al., 2023; Gleeson et al., 2022). The transformation of pervious surfaces into impervious ones (from 5% to 70%) led to reduced infiltration and shorter concentration times, resulting in sharper hydrograph peaks and faster drainage responses. Peak discharge during the 50-year post-development storm increased nearly twofold, while the 100-year post-development storm produced flow rates approximately 2.5 times higher than those observed under the 10-year pre-development condition. This outcome aligns with observations by Förster et al., 2021, Galarza-Molina et al., 2022; Oudin et al., 2018, who reported that even moderate increases in impervious coverage can disproportionately amplify urban runoff volumes.

Furthermore, the pronounced differences in time to peak between storm events 1 h and 19 min for the 50-year post-development storm compared to 1 h and 30 min for the 10-year pre-development storm illustrate the acceleration of runoff generation under urbanized conditions. These hydrologic changes directly affect the detention pond, as larger and more rapidly delivered inflows reduce the system's ability to regulate peak discharges without modification. These hydrological shifts highlight the sensitivity of small coastal catchments to both land-use change and storm intensity, emphasizing the need for dynamic flood control systems capable of adapting to variable rainfall inputs. Future studies should also incorporate sensitivity analyses using longer storm durations or real rainfall events to more fully evaluate extreme-storm behavior in modified and unmodified pond designs.

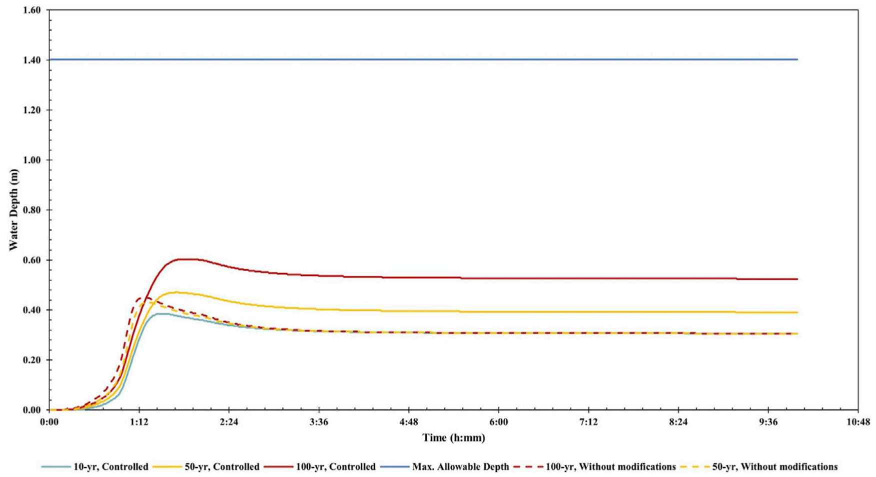

FIGURE 11
Variations in water depth for the modified detention pond under 50-year and 100-year post-development storms.

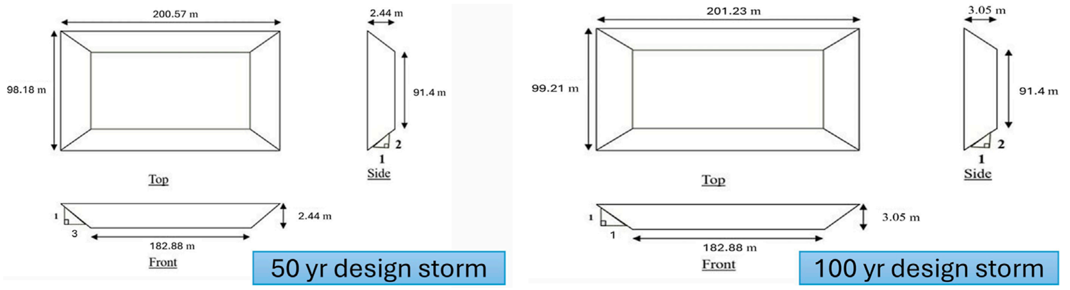

FIGURE 12
Proposed detention pond modifications for 50-year and 100-year post-development design storms.

TABLE 5 Comparison of existing vs. modified detention pond designs.

Parameter	Existing (10-year)	Modified (50-year)	Modified (100-year)
Storage volume (m^3)	17,200	44,400	55,800
Maximum water depth (m)	1.40	2.44	3.05
Orifice width (m)	3.81	3.81	3.81
Orifice height (m)	1.27	1.27	1.27
Inlet offset (m)	0.30	0.39	0.52
Purpose of modification	Baseline design	Reduce peak discharge to ~10-year level	Reduce peak discharge to ~10-year level

4.2 Performance and limitations of the existing detention basin

The baseline 10-year, 2-h pre-development storm simulation confirmed that the existing detention pond performs adequately under design conditions, effectively capturing runoff and attenuating peak discharge. However, simulations of the 50-year and 100-year post-development storms showed that, although total basin storage capacity was not exceeded, the pond became hydraulically limited under extreme rainfall conditions. Effective detention storage below the outlet elevation was rapidly utilized, resulting in earlier and higher outflows and reduced ability to regulate peak discharge. This behavior indicates increased vulnerability to downstream hydraulic stress and localized flooding under high-intensity rainfall. Similar limitations related to detention performance under extreme events have been reported by Sharior et al. (2019), Qi et al. (2025), and Yu et al. (2022) for aging stormwater infrastructure in urbanized watersheds. Hydrograph and pond stage responses further show that increasing storm return period leads to reduced retention efficiency and prolonged recovery times. During the 100-year storm, pond water levels remained elevated well after rainfall cessation, indicating delayed drainage and increased potential for sediment resuspension, which may compromise both hydraulic performance and water-quality function. These findings reinforce the need for stormwater design approaches that account for realistic rainfall temporal distributions and multiple return periods, rather than relying solely on traditional 10-year design criteria (Altobelli et al., 2024; Sharior et al., 2019).

Because the model was developed to support scenario-based comparison rather than predictive calibration, numerical results should be interpreted as approximate indicators of relative changes in peak flow and storage behavior rather than exact operational estimates. Nonetheless, the modeled trends provide useful insight into detention basin performance under increasing rainfall intensity and support evaluation of adaptive design strategies.

4.3 Effectiveness of proposed design modifications

The introduction of design modifications, specifically increasing storage capacity and optimizing the outlet orifice proved effective in reducing peak discharges during extreme storm events. The modified design achieved a marked reduction in post-development peak flow, bringing discharge values closer to pre-development levels. This demonstrates that strategic structural adjustments can substantially enhance the resilience of existing detention systems without the need for complete reconstruction. The results corroborate the conclusions of Hawley et al. (2017), Bellu et al. (2016), who emphasized that outlet control plays a pivotal role in shaping detention pond performance, particularly in regulating hydrograph recession and reducing downstream erosion potential.

While the proposed improvements enhanced hydraulic efficiency, their practical implementation is limited by the spatial and infrastructural constraints of the Edgewater–Larchmont catchment. For this reason, the study focused on increasing storage within the existing pond area and keeping the same rectangular orifice adjusting its inlet offset rather than introducing new stormwater infrastructure. As an older urban neighborhood with dense residential development, existing utilities, and a roadway situated between the pond outlet and the downstream outfall, opportunities for physical expansion are minimal. Consequently, the detention pond's performance should be interpreted within the context of a small neighborhood-scale system, as managing 50- or 100-year extreme rainfall events in such settings typically requires additional drainage and flood-control measures beyond the pond itself. These real-world constraints align with broader urban planning challenges noted by Moldenhauer-Roth et al. (2021) and Barros et al. (2025), highlighting the need to integrate hydrologic performance enhancements within existing spatial and regulatory limitations.

4.4 Implications for urban flood resilience and planning

From a broader perspective, the findings of this study contribute to the growing body of research on adaptive stormwater management under intensifying rainfall extremes. The results demonstrate that even in small urban catchments, detention ponds remain an effective yet vulnerable component of flood mitigation infrastructure. When combined with appropriate design modifications, such systems can significantly reduce peak discharges and enhance hydraulic resilience under future rainfall conditions.

However, the study also highlights the importance of designing for flexibility, ensuring that stormwater systems can accommodate a range of rainfall scenarios and respond to evolving climatic patterns. Incorporating rainfall shape and temporal distribution, rather than relying solely on total rainfall depth, proved crucial for accurately assessing detention pond performance. This aligns with emerging research advocating for shape-aware storm design in coastal cities to better capture the variability of real-world storm events. Additionally, integrating hydrodynamic modeling tools such as EPA SWMM with spatial datasets (e.g., DEM and GIS-derived catchment parameters) provides an efficient and scalable framework for evaluating existing infrastructure and guiding retrofit decisions. Such integrated modeling approaches can support municipal planners and engineers in prioritizing cost-effective, space-conscious interventions that balance hydraulic efficiency with land-use constraints. These findings extend beyond the Norfolk case, providing a transferable framework for assessing detention pond performance in other coastal and low-lying cities facing compound flood risks.

4.5 Limitations and future directions

Although this study provides important insights into the hydraulic performance of the detention pond under varying rainfall conditions, several limitations must be acknowledged. The catchment was represented as a single subcatchment to simplify the hydrologic analysis; although land use, slope, and surface roughness vary across the watershed, its small size suggests that detention-pond parameters such as storage volume, outlet characteristics, and initial water level are likely to exert a greater influence on model outputs than additional subcatchment subdivision. Nevertheless, a more detailed division of the catchment based on land-use differences, topographic gradients, and drainage outlet locations would improve spatial accuracy in future model applications. A formal sensitivity analysis was not conducted, but future work should evaluate the relative influence of key parameters such as pond storage capacity, initial water depth, infiltration rates, and outlet hydraulics by systematically varying them.

The detention pond itself was modeled as a perfectly rectangular basin, whereas field observations indicate some geometric irregularities that may slightly influence actual storage and flow distribution. Several geometric inputs were derived from Google Earth Pro and ArcGIS Pro, which may introduce minor spatial measurement uncertainties. Additionally, smaller inflow pathways and secondary drainage connections were excluded, potentially leading to modest underestimation of runoff volumes during extreme rainfall events. Each simulation also assumed a dry initial condition with an empty pond; antecedent moisture or residual storage both of which influence real-world performance were not incorporated. Model parameters were selected using available site information and values commonly reported for similar urban catchments, as full calibration was not feasible due to limited observational data. Therefore, the quantitative performance improvements reported here should be viewed as approximate values that reflect relative scenario differences rather than calibrated predictions.

High-water boundary conditions, tidal variability, and projected sea-level rise in the receiving Lafayette River were not included, as the modeling framework was designed to isolate rainfall-driven hydrologic responses. For this reason, references to hydraulic resilience and adaptive design in the manuscript should be interpreted as qualitative indicators of relative performance under controlled scenarios rather than quantitative predictions. The comparisons between storm magnitudes illustrate general trends in how pond performance changes under more intense rainfall, while the adaptive design discussion reflects conceptual improvements observed in the model rather than prescriptive engineering recommendations.

Future research should aim to refine these limitations by employing a more spatially detailed hydrologic model that subdivides the catchment into multiple subcatchments to capture heterogeneity in surface characteristics and hydrologic behavior. The use of high-resolution elevation datasets, such as LiDAR or drone-based surveys, would enhance geometric precision and improve the volume–area–depth relationships of detention facilities. Incorporating hydrologic and hydraulic measurements would also strengthen model calibration and validation, thereby improving predictive reliability. Extending the analysis to account for minor inflows, potential tidal interactions, and long-term climate variability could provide a more comprehensive understanding of detention pond performance under future conditions. Moreover, formal calibration and validation metrics such as the Nash–Sutcliffe Efficiency (NSE) were not applied in this study, as the model was developed to support scenario-based comparison rather than predictive calibration; future work should incorporate a more detailed drainage network and NSE-based validation to strengthen quantitative reliability. In coastal environments, extreme rainfall events frequently coincide with elevated water levels in receiving rivers due to storm surge or tidal forcing, which can substantially reduce the ability of detention ponds to drain effectively. These high-water boundary conditions were not included in the present modeling framework, which isolates rainfall-driven hydrologic responses. Future studies should incorporate coupled rainfall–tide or rainfall–storm-surge interactions to better assess drainage constraints and compound flooding risks in coastal catchments. Lastly, integrating hydrologic modeling with cost–benefit and resilience-based optimization frameworks could support the development of adaptive, evidence-based stormwater management strategies tailored for coastal urban environments such as Norfolk. Future studies could also apply this adaptive modeling framework to other coastal regions to test its robustness across different hydrologic, climatic, and urban development contexts. Incorporating these advanced modeling and resilience concepts into engineering education could equip future practitioners with the analytical and design skills necessary to address complex stormwater challenges in a changing climate (Ismael, 2023). This would help establish generalizable design criteria for resilient stormwater systems in the face of climate uncertainty.

5 Conclusion

This study evaluated the hydraulic performance and resilience of an existing detention basin within the Edgewater–Larchmont catchment of Norfolk, Virginia, using the U.S. EPA Storm Water Management Model (SWMM). Simulations under pre- and post-development conditions for 10-, 50-, and 100-year, 2-h design storms were conducted to assess the basin's ability to mitigate flooding and manage runoff in a low-lying coastal urban environment. Results show that urbanization, represented by an increase in impervious cover from 5% to 70%, substantially altered the hydrologic response of the catchment. Peak discharges increased by approximately two to three times across design storms, with post-development 50-year and 100-year events producing higher and more rapid runoff peaks, reduced infiltration, shorter times to peak, and increased runoff volumes. While the existing detention basin effectively manages moderate events, it becomes hydraulically limited during more extreme storms as effective detention storage below the outlet elevation is rapidly exhausted, resulting in elevated peak outflows and delayed recovery.

Design modifications focusing on increasing effective detention storage through outlet elevation adjustment were subsequently evaluated. The modified configurations significantly improved flow attenuation, reducing post-development peak discharges during the 50-year and 100-year storms toward pre-development levels. These results demonstrate that targeted, outlet-focused retrofits can substantially enhance detention basin performance at the neighborhood scale, particularly in space-constrained urban settings.

Because this study focuses on a single, small urban catchment, the findings should be interpreted as site-specific insights into local peak-flow regulation rather than generalized prescriptions for coastal flood management. Broader flood mitigation in coastal cities typically requires integrated strategies that extend beyond individual detention facilities, including network-scale drainage upgrades, storm-surge management, and consideration of tidal influences. Moreover, the quantitative results presented here should be viewed as approximate indicators of relative performance improvement rather than exact operational estimates, due to simplified model assumptions and the absence of full calibration. Nonetheless, the modeling and assessment framework demonstrated in this study provides a practical approach for evaluating detention-basin performance and identifying feasible retrofit opportunities in similar low-lying urban environments.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

IC: Conceptualization, Data curation, Formal Analysis, Methodology, Software, Validation, Visualization, Writing – original draft. AA: Conceptualization, Data curation, Formal Analysis, Methodology, Software, Validation, Visualization, Writing – review and editing. FB:

Conceptualization, Validation, Writing – review and editing. XW: Investigation, Project administration, Supervision, Validation, Writing – review and editing. ME-U: Investigation, Validation, Writing – review and editing. DI: Investigation, Project administration, Supervision, Validation, Writing – review and editing.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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