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Identifying and Prioritizing Mitigation Options to Address Climate-Related Flooding in an Established Urban Area: A Case Study of Sophia Creek Subcatchment, Barrie, Ontario

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ABSTRACT

Climate change is increasing urban flooding frequency and intensity across eastern Canada, with flood damages representing Ontario's largest climate-related financial impact. The City of Barrie experienced major floods in 2017, 2019, and 2022, with climate projections indicating increasing frequency of high-intensity storms that will overwhelm aging infrastructure. However, infrastructure upgrades are costly, requiring systematic prioritization to maximize flood risk reduction with limited capital budgets.

Lake Simcoe Region Conservation Authority partnered with the City of Barrie to undertake a pilot study in the highly urbanized Sophia Creek catchment, evaluating how climate change could influence flood risks in the subwatershed. The study developed flood depth and inundation models under climate projections from four global circulation models for 5-, 10-, 50-, and 100-year events using an integrated 1D-2D PCSWMM modeling framework.

The Risk and Return on Investment Tool (RROIT) integrates hydrologic and hydraulic modelling outputs with GIS data to quantify flood damages and evaluate the cost-effectiveness of mitigation options under both historical and future climate conditions. RROIT reports financial metrics to identify areas of greatest risk and prioritize investments that deliver the highest return on flood resilience spending. Model outputs informed a facilitated process to identify downstream areas experiencing increased flooding under climate change and their upstream contributing areas. Conservation Authority and City staff identified potential mitigation options including structural measures (trunk sewer upgrades, stormwater management facilities), distributed approaches (low impact development), and watercourse modifications (daylighting).

Results revealed that climate change increases damages by 48-204% depending on storm frequency, with most severe impacts on frequent events. Constructing a stormwater management pond emerged as the highest-priority investment with the greatest annual damage reduction of 31%, lowest capital cost ($7.3M), highest annual savings ($7.16M/yr), shortest payback period (3.0 years), and highest return on investment (98% Internal Rate of Return (IRR), $211M Net Present Value (NPV)). Expansion of a trunk sewer, currently under construction, provides complementary benefits with 4.7-year payback and 47% IRR. This methodology provides a replicable framework for evidence-based prioritization of cost-effective flood resilience investments.

KEYWORDS: Climate change adaptation, Urban flooding, Flood risk mitigation, Cost-benefit analysis, Infrastructure planning, PCSWMM, RROIT, Average annual damage

1 INTRODUCTION

Climate change is fundamentally altering precipitation patterns globally, with profound implications for urban flood management (IPCC, 2021). In Ontario, Canada, flood damages to homes and infrastructure represent the largest financial impacts associated with climate change, surpassing all other climate-related damages combined (Warren & Lemmen, 2014). Historical climate data and future projections consistently indicate that high-intensity rainfall events are becoming more frequent, more severe, and longer in duration , placing increasing stress on aging urban stormwater infrastructure that was designed using historical climate norms rather than future conditions (Bush & Lemmen, 2019).

The City of Barrie, located in central Ontario approximately 90 km north of Toronto on the western shore of Lake Simcoe, exemplifies these challenges. Historically developed along the shores of Kempenfelt Bay, Barrie transitioned from a military outpost in the early 19th century into a transportation hub and, eventually, a commuter city within the Greater Golden Horseshoe. Much of its older urban fabric was constructed in the post-war period, before contemporary floodplain management or stormwater regulations were in place. Today, Barrie is one of Ontario's fastest-growing cities (City of Barrie, n.d.), with a population nearing 150,000, experiencing increasing pressure on its natural and built drainage systems due to urban infill and intensification.

The city experienced significant flood events in 2017, 2019, and 2022, causing extensive property damage and infrastructure strain. Media reports following the July 2022 event documented extensive road closures and damage in the city's core, reinforcing the need for anticipatory planning and investment in both grey and nature-based solutions. As climate projections indicate these intense storms will become more frequent, the city faces difficult decisions about where to invest limited capital budgets for maximum flood risk reduction.

The Sophia Creek catchment, a highly urbanized subwatershed in northern Barrie, presents a particularly complex challenge. Originally a natural creek that meandered across a glacial till plain, much of the watercourse has since been altered: sections have been buried in culverts, channelized, or straightened to accommodate development and road construction. These interventions have reduced floodplain connectivity and increased the speed and concentration of surface runoff during storm events. Combined with aging infrastructure and increasing imperviousness, this has made the area highly susceptible to pluvial and fluvial flooding. This paper presents a systematic methodology for identifying, evaluating, and prioritizing flood mitigation investments under climate change uncertainty using the Risk and Return on Investment Tool.

2 METHODOLOGY

The methodology for this study followed a structured approach to identify, evaluate, and prioritize flood mitigation investments under climate change uncertainty in the Sophia Creek subwatershed. Lake Simcoe Region Conservation Authority (LSRCA), in partnership with the

City of Barrie, developed climate-informed flood models, identified vulnerable areas and contributing sources, generated mitigation alternatives through a facilitated stakeholder process, and evaluated options using the Risk and Return on Investment Tool (RROIT). The primary objective was to assess climate change impacts on flood risk and establish a replicable framework for prioritizing cost-effective urban flood resilience investments.

The project involved several key stages: data acquisition and preprocessing; development of future climate scenarios and intensity–duration–frequency (IDF) curves; mitigation scenario identification; hydrologic and hydraulic model construction and scenario-specific modifications; flood inundation analysis; RROIT input preparation and damage assessment; and mitigation scenario evaluation. All steps were guided by municipal and conservation authority technical standards and informed by current hydrologic science.

2.1 Study Area

The Sophia Creek subwatershed drains approximately 470 hectares in northern Barrie, Ontario, and is characterized by dense urban development with a mix of residential, commercial, institutional, and transportation land uses and extensive impervious cover. The watercourse flows southwest toward Lake Simcoe through a combination of straightened open channels and enclosed storm sewer infrastructure, resulting in frequent system overtopping and overland flooding during intense rainfall events.

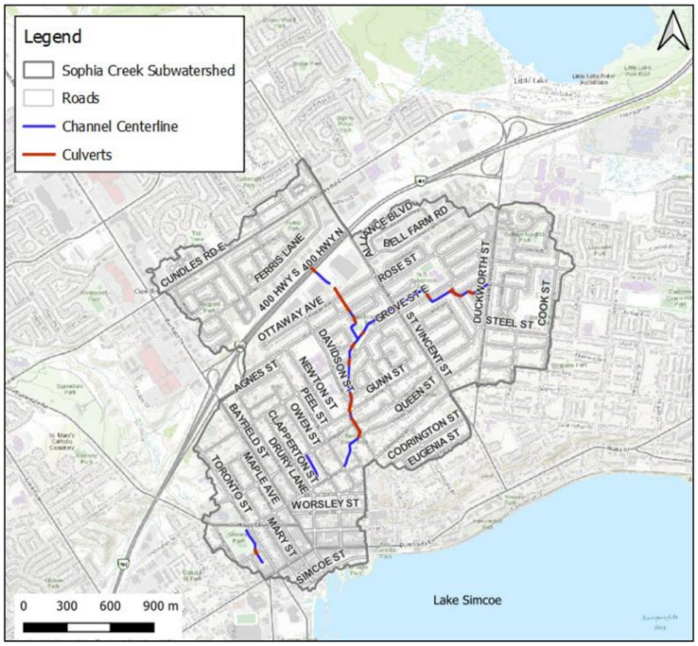

Figure 1. Sophia Creek Subwatershed

2.2 Climate Change Scenarios and Design Storms

Climate change scenarios were developed using downscaled global climate model projections from the Government of Canada's Climate Scenarios portal (CMIP6, BCCAQv2). The analysis focused on the SSP5-8.5 high-emission scenario to assess flood risk under a severe future climate pathway.

Projected changes in mean annual temperature between a historical baseline (1979–2014) and a future period (2021–2050) were calculated for available global climate models. Models were grouped into quartiles representing increasing levels of warming, and one representative model from each quartile was selected to capture a plausible range of climate futures.

Changes in extreme precipitation were estimated using temperature-based scaling consistent with the Clausius–Clapeyron relationship and national guidance (Environment and Climate Change Canada, 2023). These scaling factors were applied to regional Intensity–Duration–Frequency (IDF) relationships obtained from the Western University IDF_CC tool to generate climate-adjusted design storms for 5-, 10-, 50-, and 100-year return periods. These climate-informed design storms were used as inputs for all hydrologic and hydraulic simulations.

The scaling relationship is expressed as follows (Resilient Consulting Corporation, 2025):

$$Rp = Rc \times 1.07\Delta T \qquad (1)$$

where Rp represents future precipitation intensity for a given duration and return period, Rc represents historical precipitation intensity for the same duration and return period, and ΔT represents the projected change in mean annual temperature (in °C).

2.3 Mitigation Scenario Development

Mitigation scenarios evaluated in this study were derived from preferred alternatives identified in the Sophia Creek Watershed & Mulcaster Drainage Area Environmental Assessment Update (C.C. Tatham & Associates Ltd., 2017), completed under the Schedule ‘B’ Municipal Class Environmental Assessment process. That assessment identified flooding under both minor and major storm events and evaluated a range of flow reduction, conveyance, and restoration-based solutions through a multi-criteria framework.

A facilitated workshop involving Lake Simcoe Region Conservation Authority staff, City of Barrie engineers, and technical specialists was used to select a subset of Environmental Assessment-recommended alternatives for evaluation under climate change conditions. Preliminary flood mapping from the baseline storm sewer model was used to identify downstream flood-prone areas and their upstream contributing sources, enabling targeted selection of mitigation measures.

Seven scenarios were evaluated:

- **Scenario 1:** Existing infrastructure under historical climate conditions.
- **Scenario 2:** Climate change baseline representing the most severe warming scenario (Q4).
- **Scenario 3:** Stormwater management pond providing upstream storage (Q4).
- **Scenario 4:** Trunk storm sewer upgrade addressing downstream conveyance constraints (Q4).
- **Scenario 5:** Distributed Low Impact Development implementation (10% coverage) (Q4).
- **Scenario 6:** Watercourse daylighting along a constrained urban reach (Q4).

- **Scenario 7:** Combined trunk sewer upgrades (Q4).

Together, these scenarios represent a range of storage-based, conveyance-based, distributed, and restoration-oriented flood mitigation strategies.

2.4 Hydrologic and Hydraulic Modelling

Flood hazard modelling was conducted using an integrated one-dimensional–two-dimensional (1D–2D) PCSWMM framework, building on the City of Barrie's existing storm sewer model. The 1D component represents subsurface storm sewer conveyance, while the coupled 2D domain simulates overland flow and surface flooding, enabling representation of both piped and surface flow processes within a partially enclosed urban system. Model development followed standard municipal practice and PCSWMM guidance (CHI Water, 2021).

Design storm simulations were conducted for return periods ranging from 5 to 100 years. The model incorporated updated storm sewer, culvert, and channel data and LiDAR-derived surface elevations, with boundary conditions established at Lake Simcoe using a fixed water level. Model performance was evaluated through comparison with an independent HEC-RAS hydraulic model for the 100-year design event, and quality assurance procedures confirmed numerical stability, network connectivity, and acceptable mass balance prior to analysis.

2.5 Flood Damage and Economic Assessment

Flood damages and cost–benefit analyses were conducted using the Risk and Return on Investment Tool (RROIT), which integrates hydraulic model outputs with GIS-based exposure data to quantify flood damages and evaluate mitigation effectiveness. In this study, the RROIT was applied using flood mapping outputs from the integrated 1D–2D PCSWMM model to assess climate-driven flood risk and compare mitigation scenarios.

2.5.1 Building Damage Estimation

The RROIT relies on depth–damage curves derived from the Provincial Flood Damage Assessment Study for Alberta (IBI Group and Golder Associates, 2015), subsequently adapted for Ontario conditions. These depth–damage relationships were applied to buildings within the modeled floodplain by intersecting flood extents and water surface elevations with building footprints.

Buildings were classified using LSRCA land-use data, and appropriate depth–damage curves were assigned based on building type. Flood damages were calculated conservatively using standardized elevation offsets and depth–damage relationships, reflecting typical residential and non-residential construction in Ontario.

Residential damage values were adjusted to 2025 dollars using an 85% inflation factor based on Statistics Canada construction price indices (Statistics Canada, 2025).

2.5.2 Economic Performance Metrics

Economic performance was evaluated using Average Annual Damage (AAD), calculated as probability-weighted damages across return periods. Investment performance metrics included internal rate of return (IRR), representing the discount rate at which net benefits equal costs, and net present value (NPV), representing the discounted value of benefits minus costs over the asset life.

Capital costs were based on inflation-adjusted Environmental Assessment estimates, with infrastructure service lives consistent with municipal practice.

3 RESULTS

3.1 Climate Change Impacts on Flood Damages

Climate change dramatically increases flood damages across all return periods, with particularly severe impacts on more frequent storm events. Under the most severe climate scenario (Q4), 5-year storm damages increase by 204% (from $20.8M to $63.1M), while 100-year storm damages increase by 48% (from $157.0M to $232.4M). This pattern reflects the compounding effect of increased rainfall intensity on infrastructure that is already stressed during design events.

The results demonstrate that climate change does not simply shift the probability distribution of storms; it fundamentally alters the damage-frequency relationship in ways that disproportionately affect more frequent events that drive long-term expected annual damages. Climate change (Q4) will expose 69-281% more buildings to flooding, with the 5-year event seeing the number of buildings affected increase from approximately 41 to 157.

Table 1. Climate change impact on flood damages (Q4 Scenario vs Existing Conditions)

Return Period	Existing Damages ($M)	Q4 Climate Damages ($M)	Buildings Affected (Existing)	% Increase
5-year	$20.8	$63.1	41	+204%
10-year	$47.3	$102.5	121	+117%
50-year	$124.7	$197.1	303	+58%
100-year	$157.0	$232.4	392	+48%

3.2 Mitigation Scenario Performance

Table 2 presents the physical and economic performance of each mitigation scenario under the most severe climate scenario (Q4). The SWM pond at MacMorrison Park (Scenario 3) provides the greatest overall benefit with the lowest AAD of $16.0M, representing a 31% reduction from the climate baseline. This scenario performed best in four of five return periods (5-, 10-, and 100-year events), with damage reductions ranging from 15.1% to 47.4%.

The Owen Street trunk sewer upgrade (Scenario 4, currently in construction) provides the best performance for the 50-year event with 17.5% damage reduction. Scenarios 4 and 7 show nearly identical results, confirming that the Clapperton Street trunk adds minimal benefit beyond Owen Street alone. Notably, the daylighting scenario (Scenario 6) increases damages across all return periods, with AAD increasing by $903,024 compared to the climate baseline. This finding indicates that removing the culvert increases flood depths in some areas despite improved conveyance.

Table 2. Mitigation scenario performance under Q4 climate scenario

Scenario	Current AAD ($/year)	AAD Reduction vs Baseline	100-yr Damage ($M)	Ranking
Scenario 1 (Existing)	$8.4M	Reference	$157.0	N/A
Scenario 2 (Climate Q4)	$23.2M	Baseline	$232.4	Baseline

Scenario	Current AAD ($/year)	AAD Reduction vs Baseline	100-yr Damage ($M)	Ranking
Scenario 3 (SWM Pond)	$16.0M	-$7.16M	$197.3	1
Scenario 4 (Owen Trunk)	$18.1M	-$5.13M	$201.5	2
Scenario 5 (LID 10%)	$18.7M	-$4.52M	$213.1	4
Scenario 6 (Daylighting)	$24.1M	+$0.90M	$244.7	Not Recommended
Scenario 7 (Both Trunks)	$18.1M	-$5.14M	$201.5	3

3.3 Spatial Damage Analysis

Aggregation plots from RROIT reveal where damage concentrations spatially occur across the subwatershed, representing the cumulative effect of upstream subcatchment contributions. Under the Q4 climate scenario, damage concentrations are highest in the downstream portions of the watershed near Bayfield Street and along the main Sophia Creek corridor, where flooding from surcharging storm sewers affects adjacent properties.

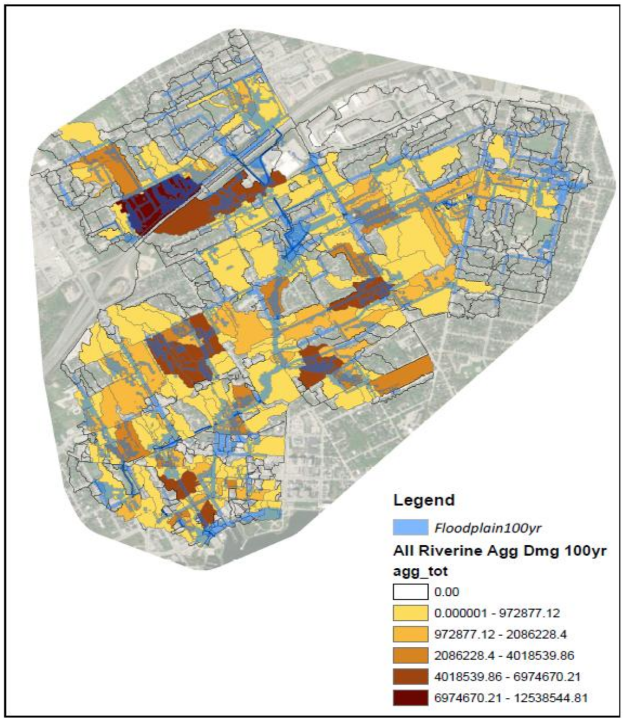

Figure 2. Damage Aggregation Plot for Scenario 3 (SWM Pond) under 100-Year Q4 Climate Event

Re-aggregation plots identify which individual subcatchments contribute to downstream flooding, providing insight into retrofit opportunities beyond where flooding occurs. For Scenario 3 (SWM Pond), the re-aggregation analysis shows significant damage reduction in subcatchments downstream of MacMorrison Park, demonstrating the pond's effectiveness in attenuating peak flows that would otherwise cause downstream property damage.

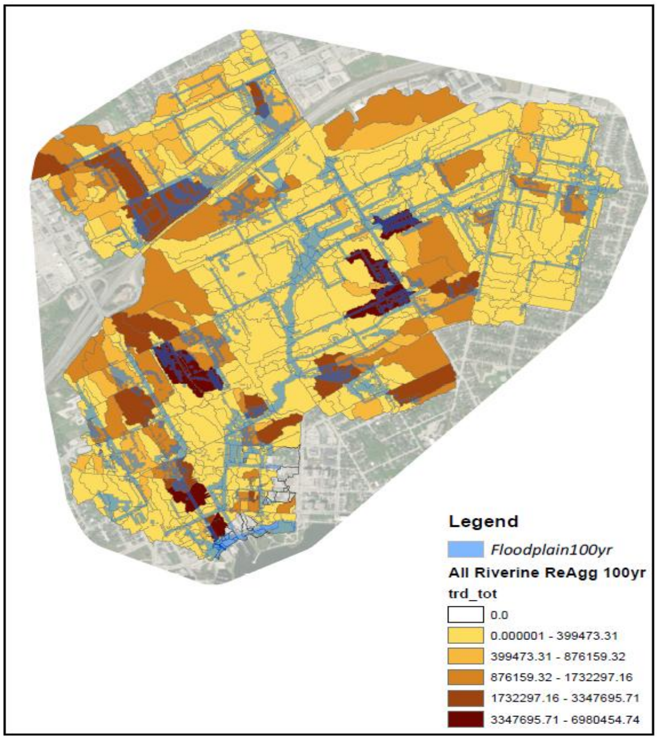

Figure 3. Damage Re-Aggregation Plot for Scenario 3 (SWM Pond) showing Contributing Subcatchments

Building-level riverine damage results for Scenario 3 (Stormwater Management Pond) indicate that the facility protects 69 buildings and reduces damages by $35.10M compared to the Q4 baseline. The spatial distribution of protected buildings is shown below:

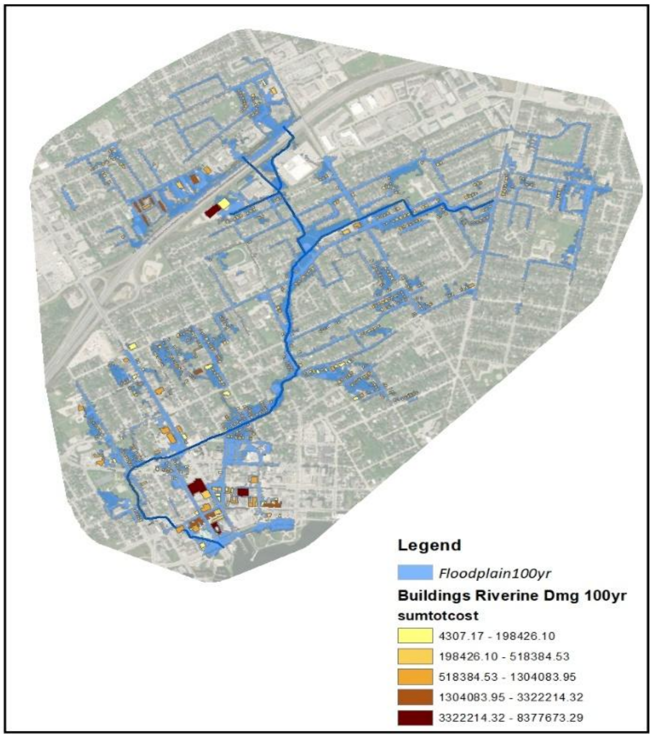

Figure 4. Building Riverine Damage for Scenario 3 (SWM Pond)

3.4 Average Annual Damage Analysis

Average Annual Damage (AAD) provides a probability-weighted measure of expected flood damages that accounts for the full range of storm frequencies. Under existing conditions, AAD is \$8.4M per year. Climate change (Q4) increases this to \$23.2M per year—a 176% increase that reflects the combined effect of more intense storms across all return periods.

While no mitigation scenario fully restores damages to pre-climate change levels, Scenarios 3, 4, 5, and 7 all substantially reduce impacts compared to the climate baseline. Scenario 3 (SWM Pond) achieves the greatest AAD reduction of \$7.16M per year, followed by Scenario 7 (Both Trunks) at \$5.14M and Scenario 4 (Owen Trunk) at \$5.13M. The LID scenario provides a more modest \$4.52M reduction. Industrial/Warehouse buildings emerged as the most vulnerable building type, with the highest damage per building across all return periods.

3.5 3.5 Cost-Benefit Analysis

Return on investment metrics were calculated using RROIT's cost-benefit module, comparing AAS against capital costs over each scenario's service life (Table 3). From an economic perspective, Scenario 3 (SWM Pond) emerges as the clear winner with the lowest capital cost (\$7.31M), highest annual savings (\$7.16M/yr), shortest payback period (3.0 years), and highest internal rate of return (97.86%). The NPV of \$211M over the 75-year service life represents exceptional value for this investment.

Table 3. Cost-benefit analysis of mitigation scenarios

Scenario	Capital Cost ($M)	Annual Savings ($/yr)	Payback (yrs)	IRR (%)	NPV ($M)
Sc 3 (SWM Pond)	$7.31	$7.16M	3.0	97.86	$211
Sc 4 (Owen Trunk)	$10.89	$5.13M	4.7	47.13	$144
Sc 7 (Both Trunks)	$21.79	$5.14M	8.6	23.60	$128
Sc 5 (LID 10%)	$62.40	$4.52M	32.5	7.21	$50
Sc 6 (Daylighting)	$7.63	-$0.90M	Never	N/A	-$39

The next best economic option is Scenario 4 (Owen Street Trunk Sewer), which is already under construction. With a capital cost of \$10.9M, annual savings of \$5.13M, payback period of 4.7 years, IRR of 47.13%, and NPV of \$144M, this scenario provides strong return on investment. Scenario 7 (Both Trunks) has a capital cost of \$21.8M with nearly identical annual savings (\$5.14M) and a very similar spatial pattern of flood damage reduction compared to Scenario 4, resulting in a longer payback period (8.6 years), lower IRR (23.60%), and lower NPV (\$128M)—confirming that the Clapperton Street trunk provides minimal incremental benefit beyond Owen Street alone.

Scenario 5 (LID) requires the highest capital investment (\$62.4M) with modest annual savings (\$4.52M), resulting in a 32.5-year payback period and NPV of \$50M. While still providing positive returns, the extended payback period reflects the distributed nature and higher implementation costs of watershed-wide LID retrofits. Scenario 6 (Daylighting) produces negative annual savings (-0.9M/ yr) and negative NPV (-\$39M), making it economically unviable as a standalone flood mitigation measure. This scenario actually increases flood damages rather than reducing them.

4 DISCUSSION

This study demonstrates a systematic approach for prioritizing flood mitigation investments under climate change uncertainty and highlights several implications for municipal adaptation planning.

Integrating climate projections into flood risk assessment substantially alters the economics of flood management. Projected increases in damages across return periods indicate that reliance on historical climate data can significantly underestimate future risk and lead to underinvestment in adaptive infrastructure.

Mitigation performance varied widely across intervention types, underscoring the importance of rigorous quantitative evaluation. The superior performance of the stormwater management pond reflects its upstream location, available storage capacity, and ability to attenuate peak flows affecting multiple downstream areas. In contrast, other interventions provided more limited or localized benefits, reinforcing the need for evidence-based prioritization rather than qualitative preference.

The daylighting scenario evaluated in this study illustrates that flood risk reduction should not be assumed as an inherent outcome of restoration projects. Under the specific site conditions and conceptual design assessed, daylighting increased flood depths in some areas due to constrained urban geometry and limited floodplain capacity. This finding is site- and design-specific and emphasizes the importance of context-sensitive, hydraulically informed evaluation of nature-based solutions.

Finally, the integration of PCSWMM with the Risk and Return on Investment Tool represents a practical methodological advancement for urban flood risk assessment in partially enclosed catchments. By capturing both storm sewer surcharging and overland flooding processes, this approach supports more reliable damage estimation and investment prioritization under climate change.

5 CONCLUSIONS

This study developed and applied a systematic framework for prioritizing flood mitigation investments under climate change uncertainty in the Sophia Creek catchment, Barrie, Ontario. Climate-informed flood modeling indicates that damages could increase by 48–204% across return periods under a high-emission scenario, highlighting the growing long-term liability associated with more frequent flood events.

Five mitigation scenarios were evaluated using integrated 1D–2D PCSWMM modeling and the Risk and Return on Investment Tool. Among these, the stormwater management pond emerged as the highest-priority investment, achieving a 31% reduction in Average Annual Damage and performing best across most return periods. While combined mitigation strategies produced greater absolute damage reductions, they offered diminished marginal returns relative to the pond's standalone performance.

Overall, the results underscore the importance of rigorous, quantitative evaluation in climate adaptation planning. The integrated PCSWMM–RROIT framework provides municipalities with a replicable, evidence-based approach for prioritizing cost-effective flood resilience investments and avoiding reliance on qualitative or ad hoc decision-making. As climate change continues to intensify flood risk, such systematic frameworks will be increasingly critical for effective municipal infrastructure planning.

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