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Optimizing Green Infrastructure for Flood Mitigation and Enhancing Disaster Resilience - Hoboken NJ Case study

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With storm events expected to increase in frequency and intensity in Northeastern U.S., Hoboken's vulnerability to disruption from even minor rain events, and rising concerns towards environmental impact, Hoboken is in dire need of new sustainable flood mitigation techniques. Green Infrastructure (GI) may offer environmentally friendly alternatives to typical flood mitigation techniques but requires more attention to garner- ing public support and assessing the feasibility of these measures. This study seeks to replicate and improve upon previous studies designed to assess social impact and feasibility of implementing Green Infrastructure for disaster resilience in Hoboken. The focus is on the evaluation and optimization of combinations of GI methods, using stormwater runoff reduction and total capital cost as metrics.

Keywords: Flood Mitigation, Disaster Resilience, Green Infrastructure, Sewer Network, Stormwater Run-off, Cost- effectiveness, Optimization, Hydrological Modeling, Climate Change.

1. Introduction

Flooding is a significant and recurrent issue in urban environments, with coastal cities like Hoboken, New Jersey facing persistent challenges due to their geographical location and high population density. More than two-thirds of the land is vulnerable to flooding during both small and largescale storm events, as evidenced by Hoboken's history of flooding, especially during Superstorm Sandy [1] . As storms become more frequent and intense due to climate change, traditional infrastructure alone proves insufficient in managing urban flooding effectively. This necessitates the exploration and implementation of innovative flood mitigation strategies that not only address immediate flooding concerns but also enhance long-term disaster resilience.

Green infrastructure (GI) has emerged as a promising approach and promotes urban livability through a planned network of natural and semi-natural areas along with other environmental features that are designed and managed to pro- vide a wide range of ecosystem services [2] [3]. In this study, we focus on evaluating three Green Infrastructure strategies — 1) Stormwater Infiltration Planters and Street Trees (ROWs), 2) Rain Gardens, and 3) Permeable Interlocking Concrete Pavers in mitigating flooding in Hoboken as there are the most economically viable for the city. By measuring the following metrics: runoff reduction, cost-effectiveness, potential water storage, and useful life, this study seeks to provide a comprehensive assessment of these strategies to mitigate flooding and enhance disaster resilience. Infrastructural damage, property loss, and public safety risks are significant concerns due to flooding risk in Hoboken. The frequent inundation of streets and homes disrupts daily life, causes economic losses, and can lead to long-term environ- mental damage. Figure 1 shows that currently, 81.7 percent of properties in Hoboken face flooding risks, with the figure projected to rise to 87 percent over the next 30 years [4]. Addressing this problem is important for improving the quality of life for residents and ensuring the city's sustainability. Implementing effective flood mitigation strategies using Green Infrastructure can reduce the economic burden of flood damage, improve public health and safety, and contribute to a more resilient urban environment.

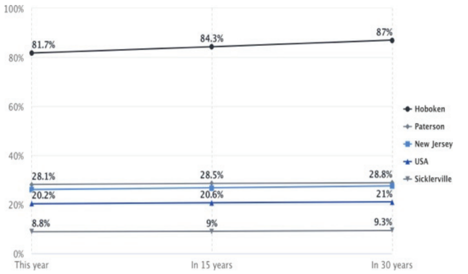

Fig. 1. Percentage of properties susceptible to flooding [4]

Traditional approaches to stormwater management, such as gray infrastructure, have proven inadequate in managing the increasing stormwater volumes resulting from more intense and frequent storms. Previous research that explored the use of green infrastructure (GI) to enhance stormwater management focused on metrics such as run-off and public acceptance [5]. However, it did not provide an evaluation of their cost effectiveness and useful life. The previous study utilized a Storm Water Management Model (SWMM) to simulate the selected GI in various scenarios [5]. SWMM is a complex software program that allows for accurate simulations of rain behavior through water management systems [6]. This study utilizes SWMM in a similar approach to the previous study of modeling GI options in the study area under a range of rain intensities.

2. Background

Climate conditions are changing drastically worldwide, including the east coast of the United States of America in which the study area is located. The increasing frequency and severity of inclement weather is resulting in unprecedented costs in damages. In 2022, weather conditions resulted in damage amounting to over one billion dollars [7]. Hoboken is particularly vulnerable to flooding due to its high population, inadequate water management systems, and intense localized rainfall [8]. Due to Hoboken's vulnerability to flooding from even minor rain events, it has been the subject of various studies for Green Infrastructure methods. Hoboken, NJ was chosen as the study area for this research to replicate and add to the findings of the previous studies.

Green infrastructure (GI) employs non-structural measures that leverage natural processes to manage floodwaters. Examples of GI include floodplain reconnection, permeable surfaces, and urban green spaces. Green systems enhance resilience by reducing exposure and vulnerability to floods and adapting more effectively to environmental and social changes compared to purely traditional grey infrastructure [2] [3].

A 2017 study from the Hydrological Sciences Journal [9] explored the dynamics of flood risk and community resilience through socio-hydrological modelling, comparing green and technological systems using data from Bangladesh and Rome. Their research illuminated the strengths and weaknesses of each approach, offering critical insights for policy implications across diverse socio-economic contexts. These tools are categorized based on their capabilities to address stormwater management, economic analysis, or both aspects. Among the reviewed tools are RE- CARGA, P8 Urban Catchment Model, EPA SWMM, WERF BMP and LID Whole Life Cycle Cost Modelling Tools, GI Valuation Toolkit, CNT National Green Values Calculator, EPA SUSTAIN Model, and MUSIC [10]. These modelling tools are instrumental in evaluating the performance and cost-effectiveness of GI solutions, thereby assisting decision- makers in implementing sustainable flood mitigation strategies. These tools vary in their capabilities, required inputs, and generated outputs, catering to different user needs and project scales.

3. Modelling and Simulations

A previous study implemented the hydrologic model of the Hoboken sewer system and selected GI in an open-source software developed by the U.S Environmental Protection Agency (EPA) Storm Water Management Model (SWMM) version 5.1.014 [5]. In this study, the hydrologic model was implemented in version 5.2.4, released in 2023. SWMM allows for backdrop images to be uploaded into the project to function as a background structure for the model to be built over. Besides the alignment of the model, the backdrop image has no interaction with the rest of the model [6].

3.1. *New Calibrations*

A simplified image of Hoboken provided by The National Oceanic and Atmospheric Administration (NOAA) was imported into SWMM as the backdrop [11]. The image shows streets, bodies of water, and few textual labels. The longitudinal and latitudinal coordinates for the upper right and lower left corners of the map were entered for calibration of the model's dimensions. The upper right used an X-coordinate of 40.758966 degrees and a Y-coordinate of - 74.022116 degrees. The lower left used an X-coordinate of 40.730947 degrees and a Y-coordinate of -74.048047 degrees [11].

Three rain gages were created for small, medium, and large rain events. The data for the gages may either be selected from a database within SWMM, imported through a format compliant file, or entered in the creation of a time series [6]. The precipitation data for the gages was selected by evaluating the maximum precipitation per month during 2023 shown in Figure 2 [12] [13].

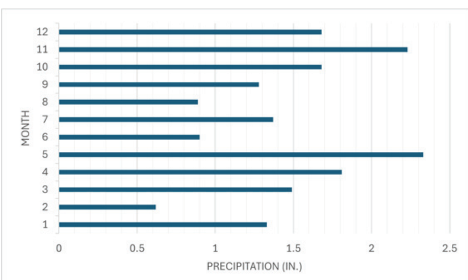

Fig. 2. 2023 Monthly Maximum Precipitation Data

The precipitation data for the large rain event was derived from an average rain event of May which was the month in 2023 with the highest maximum precipitation. Similarly, the precipitation data for the small rain event was derived from an average rain event of February which was the month in 2023 with the lowest maximum precipitation. The data for the medium intensity rain event was selected by averaging the highest and lowest maximum monthly precipitation values to create a reference value of 37.465 millimetres. March, the 2023 month with the closest maximum monthly precipitation to this value, provided the data from an average rain event for the medium intensity rain event.

3.1.1. *Selected GI*

In this study, we have used three Green Infrastructure options to evaluate their effectiveness in managing stormwater and mitigating flooding across different areas in Hoboken. These options include:

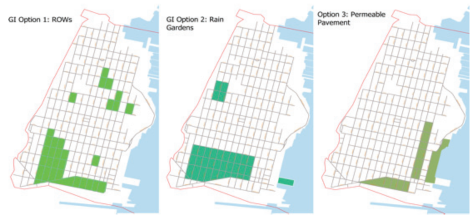

Fig. 3. GI Options

GI Option 1 - Stormwater Infiltration Planters and Street Trees (so-called Right-Of-Ways, ROWs): A stormwater infiltration planter is a designated area designed to capture and treat stormwater and consists of layers of vegetation, soil, and plant roots that work together to filter and manage the stormwater [14]. Previous study demonstrated that ROWs effectively reduced and delayed runoff volumes during rain events due to their combined capacity for storage and their expansive area. For this study, we selected the same locations as the previous study for GI implementation of 41 ROWs, as shown in Figure 3 [5].

GI Option 2 - Rain Gardens: A rain garden is a sunken area in the landscape designed to capture rainwater from sources like roofs, driveways, or streets and let it absorb into the ground [15]. Previous studies have shown that rain gardens are effective in managing stormwater by reducing flood peaks, enhancing groundwater recharge, improving water quality, and promoting biodiversity and aesthetic appeal [16]. However, other research indicates that their effectiveness can be significantly impacted by maintenance issues and soil con- ditions as evaluated through visual inspections, infiltration rate testing, and synthetic drawdown testing

[17]. The locations for implementation are shown in Figure 3.

GI option 3 - Permeable Pavement: Traditional pavement alternatives like pervious asphalt, pervious concrete, interlocking pavers, and plastic grid pavers can help reduce runoff by letting rain and snowmelt seep through to underlying soil and gravel layers [18]. Figure 3 shows the locations for GI implementation. Permeable pavement systems effectively manage stormwater runoff, improve water quality, and con- tribute to sustainable drainage and renewable energy solutions. However, their adoption is limited due to challenges related to design, and maintenance [19] [20].

3.1.2.*metrics of Assessments*

Stormwater Run-off Volume: Stormwater runoff is an essential contributing factor to the selection of Green Infrastructure (GI) because the reduction of runoff is the primary function and goal of GI implementation. This study seeks evaluation of Green Infrastructure as a potential solution to the high vulnerability to disruption from minor rainfall of densely populated areas such as Hoboken [8]. The reduction of stormwater runoff must be significant enough to provide prevention and mitigation of rainfall induced damages in the urban study area. Additionally, the amount of stormwater runoff reduced by the implementation of the GI Option must equate to or offset its projected cost. These conditions serve the purpose of justifying the associated costs and efforts of installation.

Cost Analysis: Cost is an important factor in selecting green infrastructure (GI) strategies because it directly impacts project feasibility and sustainability. It encompasses not just initial construction but also life cycle expenses, including planning, design, installation, maintenance, and replacement. A comprehensive cost analysis should consider these expenses alongside the infrastructure's performance and the multiple benefits it provides, such as environmental, economic, and community advantages [21]. Table 1 shows cost analysis for the different GI options [22]. 3)

Table 1. Cost Analysis of Green Infrastructure

GI	Capital Cost	Annual Operations Maintenance Cost
1	$29.92/cu.ft.	5%
2	$28.05/cu.ft.	8%
3	$2.62/cu.ft.	3%

Useful Life: The useful life of GI is critical as it influences long-term sustainability and cost-effectiveness. A longer useful life reduces the frequency and cost of replacements and maintenance while also ensuring consistent performance and prolonged environmental, economic, and community benefits. Table 2 shows useful life for the different GI options [22].

Table 2. Useful life Green Infrastructure

GI	Useful Life
1	20-50 years
2	20-50 years
3	20-40 years

Potential Water Storage: The effectiveness of green infrastructure in managing stormwater and reducing flooding depends on its potential water storage capacity. By providing adequate storage, the green infrastructure can mitigate runoff, enhance groundwater recharge, and contribute to sustainable water management. Table 3 shows the parameter values used for calculation of potential water storage for the different GI options [5] [23].

Simulation Scenarios: The previous study simplified the modeled study area, focusing the most detail in the region of Hoboken with the highest population density and that suffers the greatest impact from rain events [5]. Figure 4 shows this study's hydrological model of the Hoboken sewer system which holds a consistent level of detail throughout the city, regardless of population density or vulnerability. Each block is represented by a sub-catchment which drains either to the manhole located in the upward right of the block or the nearest manhole. Each manhole is represented by a junction specified by an invert elevation calculated from the average of the manhole of that vicinity detailed in a sewerage map provided by the North Hudson Sewerage Authority. The original Hoboken sewer map included over 6,000 manholes [19]. Through the method of averaging manholes by intersection, the number of manholes in the SWMM model was reduced to 225 while maintaining a level of accuracy. The invert elevations for each junction varied from

0.0 to 33.2 meters. A total of 12 scenarios were run, with each option and the model before implementation of any option under three rain events of small, medium, and large intensities. The rain event data was derived from 2023 to best simulate current and future rain events [12] [13].

Table 3. Parameter Values

Parameter	GI 1	GI 2	GI 3
Surface			
Area	35,668	10,042	26,306
Berm Height (m)	0.4	0.5	0
Vegetation (%)	0.15	0.15	0
Roughness (Manning's coefficient)	0.24	0.3	0.1
Slope (%)	1.0	0	1.0
Soil			
Thickness (m)	0.9	0.3	0.1
Porosity (-)	0.35	0.4	0.35
Field Capacity (-)	6.2	0.3	0.2
Wilting Point (-)	2.4	0.15	0.1
Conductivity, K (mm/hr)	120.6	1.9	0.5
Conductivity Slope (%)	48.0	8.0	10.0
Suction Head (mm)	0.49	3.5	3.5
Storage			
Thickness (m)	0.3	0.3	0.2
Void Ratio (-)	0.75	0.4	0.35
Seepage Rate (m/s)	0	0	0
Clogging Factor (-)	0	0	0
Drain			
Flow Coefficient, Cf	0.3613	0.3	0
Flow Exponent, n (-)	0.5	0.5	0
Offset, h (m)	0	0	0
Open Level (m)	0	0	0
Closed Level (-)	0	0	0
Bottom Layer			
Thickness (cm)	-	20	-
Void Fraction (-)	-	0.3	-
Roughness (Manning's Coefficient)	-	-	-
Joint Aggregate Void Ratio			
Joint Aggregate Void Ratio (%)	-	-	35
Bedding Layer			
Bedding Layer Thickness (mm)	-	-	50
Bedding Layer Void Ratio (%)	-	-	35
Base Layer			
Base Layer Thickness (mm)	-	-	100
Base Layer Void Ratio(%)	-	-	35
Subbase Layer			
Subbase Layer Thickness (mm)	-	-	200
Subbase Layer Void Ratio(%)	-	-	35

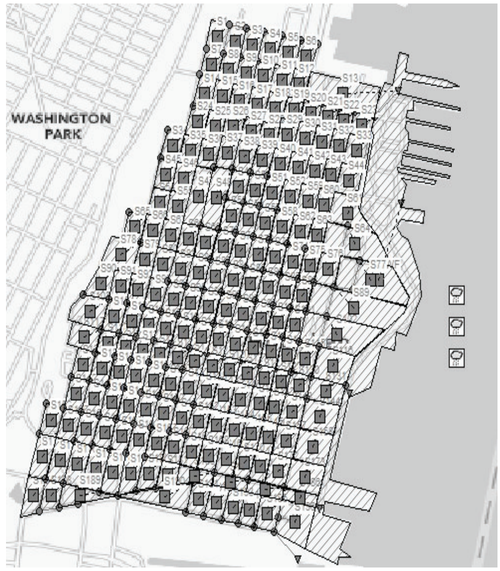

Fig. 4. SWMM Hoboken Sewer Network

4. Results

Each run of the SWMM simulation is able to produce a number of result summaries and reports. The Sub catchment Runoff Summary Results table includes a wide range of runoff data from the simulation's run. From this report, the total runoff in millimetres was collected for all sub catchments. Aside from the sub catchment representing the waterfront, all sub catchments are roughly the same size and were treated equally in calculations. An average runoff of all sub catchments, excluding the waterfront sub catchment, was calculated for the three levels of rain intensity.

GI Option 1:

1) Stormwater Run-off Volume: The calculated average sub catchment runoff for the small, medium, and large intensity rain events for GI Option 1: Stormwater Infiltration Planters and Street Trees are 8.13, 42.01, and 56.57 millimetres, respectively.

2) Cost Analysis: The cost was calculated by multiplying the capital cost per cubic foot by the total volume required which was derived from the given area. Annual operations and maintenance costs were then determined as 5% of the total capital cost [17].

3) Potential Water Storage: The theoretical potential water storage was calculated by summing the water storage capacities of the soil

layer and the storage layer for a single ROW and then, multiplying this total by the number of ROWs. The soil and storage layer capacities were determined using their respective area, thickness, porosity, and void ratio.

GI 2: Rain Gardens
1) Stormwater Run-off Volume: The simulated stormwater runoff resulting from implementation of GI Option 2: Rain Gardens was obtained in the same manner as previously described for GI Option 1: Stormwater Infiltration Planters and Street Trees. The average runoff for all sub-catchments, excluding the waterfront sub-catchment, was calculated for the three levels of rain intensity. The calculated average sub-catchment runoff for the small, medium, and large intensity rain events for GI Option 2: Rain Gardens are 8.16, 42.13, and 56.74 millimetres, respectively.
2) Cost Analysis: The cost was calculated by multiplying the capital cost per cubic foot by the total volume required which was derived from the given area. Annual operations and maintenance costs were then determined as 8% of the total capital cost [17].
3) Potential Water Storage: The theoretical potential water storage was calculated by determining the volume of each layer—soil, storage, and bottom—based on the area and thickness. The water storage capacity for each layer was then computed using the appropriate porosity, void ratio, or void fraction, and the capacities of all layers were summed to find the total potential water storage.

GI 3: Permeable Pavement
1) Stormwater Run-off Volume: The average stormwater runoff per sub catchment for GI Option 3: Permeable Pavement was calculated through the same approach as GI Options 1 and 2. The calculated average sub catchments runoff for the small, medium, and large intensity rain events for GI Option 3 are 8.17, 42.19, and 56.83 millimetres, respectively.
2) Cost Analysis: The cost was calculated by multiplying the capital cost per cubic foot by the total volume required which was derived from the given area. Annual operations and maintenance costs were then determined as 3% of the total capital cost [17].
3) Potential Water Storage: The theoretical potential water storage was calculated by determining the volume of each aggregate layer—joint aggregate, bedding layer, base layer, and subbase layer—based on the area and thickness. Each volume was then multiplied by the corresponding void ratio to find the water storage volume, and the volumes of all layers were summed to obtain the total potential water storage.

Table 4. GI Options Results

Type	Total Area (H)	Capital Cost	O&M Cost	Water Storage (m^3)
ROWs	3.53	11,365,712	568,285	19,072
Rain Garden	1	4,974,235	397,938	3,012
Permeable Area	2.6306	741,930	22,257	3,219

Table 4 provides a comparative overview of different GI options, detailing their total area, capital cost, operational and maintenance (O&M) cost, and theoretical potential water storage capacity.

4.1 Interpretation

The Green Infrastructure Options evaluated in this study are not inherently equal in cost or projected water storage. To account for this, adjustments have been made in the interpretation of the results. In the interpretation of runoff, an adjuster was created to evaluate each option at consistent projected stormwater runoff storage. The storage adjusters for GI Option 1, GI Option 2, and GI Option 3 were .63, 1, and 1, respectively. Cost effectiveness was evaluated by the comparison of cost to the reduction in stormwater runoff (mm) per sub catchment. For this, an adjuster was added to the total capital cost that was calculated for each option. The cost adjusters for GI Option 1, GI Option 2, and GI Option 3 were 0.940, 0.056, and 0.004, respectively.

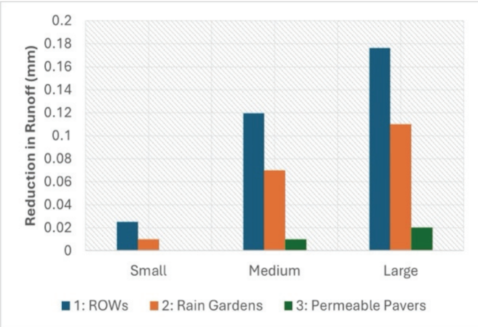

Fig. 5. Runoff Performance Per Sub-catchment

As shown in Figure 5, GI Option 1: Stormwater Infiltration Planters and Street Trees was the most effective at reducing stormwater runoff for all levels for rain intensity. GI Option 3: Permeable Interlocking Concrete Pavers performed on the opposite end with the smallest negative change in stormwater runoff per sub-catchment. Figure 6 shows that although GI Option 1: Stormwater Infiltration Planters and Street Trees was evaluated as the highest performing in stormwater reduction compared to projected storage, it has the lowest performance in cost effectiveness. GI Option 3: Permeable Interlocking Concrete Pavers has the highest performance in cost effectiveness. GI Option: Rain Gardens, falls between GI Option 1: Stormwater Infiltration Planters and Street Trees and GI Option 3: Permeable Inter- locking Concrete Pavers for cost effectiveness.

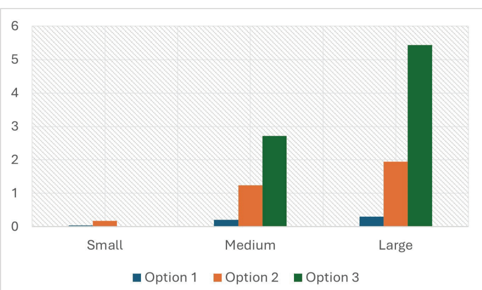

Fig. 6. Cost Performance Per Sub-catchment

Table 5 is a Pugh matrix which compares different GI options based on metrics such as runoff volume, theoretical potential water storage, cost, and life span. The analysis shows that permeable pavement has the highest overall score (2.8), indicating it may be the most effective option, followed by ROWs (2.7) and rain gardens (2.5).

Table 5. Pugh Matrix for GI Options

Metric	Weight	No GI	GI 1	GI 2 - Rain Garden	GI 3 – Permeable
Run-off Volume	0.40	0	3	2	1
Water Storage	0.20	0	4	2	3
Cost	0.30	0	1	3	5
Life Span	0.10	0	4	4	3
	Score	0	2.7	2.5	2.8

5. Conclusion and Future Work

The benefit of Green Infrastructure methods was found to increase as a function of rainfall volume. Although minor rain events are more frequent in Hoboken, weather conditions continue to worsen along the east coast. With consideration of this trend in combination with cost effectiveness, this research concludes that Permeable Pavement is the most cost- effective Green Infrastructure option of the three evaluated for the mitigation of flooding. When considering these results in future planning, it is important to note that this conclusion is derived from theoretical calculations. If theoretical calculations are to be wholly disregarded, Stormwater Infiltration Planters and Street Trees would be found to be the most effective Green Infrastructure method of the three considered.

The research conducted through this study may be applied to future work through additions and improvements that were previously discussed in the original design of the study. Transportation times during flooding can be assessed as a metric to evaluate the effectiveness of Green Infrastructure (GI) options in mitigating flood impacts and enhancing travel efficiency in urban areas. Optimization of Green Infrastructure has the potential to solve for innovative implementation that minimizes cost and socio-economic disruption while maximizing stormwater runoff storage and infiltration. A simple method for such an optimization would be the involvement of a Linear Programming (LP) problem in the evaluation of the results.

As the climate continues to change, resulting in increasing damage, it is important to invest in disaster resilience methodology [7]. A key component to disaster resilience planning is a foundation of research which seeks to test, optimize, and plan for optimal utilization.

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