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A Framework for Evaluating the Effects of Green Infrastructure in Mitigating Pollutant Transferal and Flood Events in Sunnyside, Houston, TX

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Abstract: There is a growing and critical need to develop solutions for communities that are at particular risk of the impacts of the nexus of hazardous substances and natural disasters. In urban areas at high risk for flooding and lacking proper land-use controls, communities are vulnerable to environmental contamination from industrial land uses during flood events. This research uniquely applied a series of landscape pzerformance models to evaluate such associations including (1) the Green Values National Stormwater Calculator, (2) the Value of Green Infrastructure Tool, and (3) the Long-Term Hydrologic Impact Assessment Model. This paper presents a framework for combining landscape performance models, which are often only individually applied, to evaluate green infrastructure impacts on flood mitigation and pollutant transfer during flooding events using the Sunnyside neighborhood in Houston, Texas, USA, as a case site. The results showed that the plan reduced the risk of flooding, decreased stormwater runoff contaminants, and provided a possible direction to protect vulnerable communities.

Keywords: landscape performance; green infrastructure; stormwater; resilience; equity

1. Introduction

Globally, nearly 2.4 billion people live within 100 km of a coastline, with 600 million living in coastal regions less than 10 m above sea level [1]. These populations face resilience challenges due to climate change and the increased frequency and intensity of natural hazards [2]. In the United States, 8% of counties are characterized as coastal, occupying 39% of the total U.S. population; 52% live in counties designated as coastal watersheds [3]. Populations have increased in coastal counties since 1970 and are projected to continue to grow at nearly three times the national growth average [4,5].

Green infrastructure (GI), which is the interconnected network of green space that includes natural ecological features, parks, landscaped areas, trees, and vegetation [6], has been shown to assist in reducing the impacts of flooding in urban areas [7]. According to the U.S. Environmental Protection Agency (EPA), GI is an "adaptable term used to describe an array of products, technologies, and practices that use natural systems (or engineered systems that mimic natural processes) to enhance overall environmental quality and provide utility services" [8]. The EPA suggests that green infrastructure could include innovative ways to reduce the volume of urban stormwater runoff. For example, GI both provides community benefits and reduces the need for additional public spending on storm drains [9]. Unfortunately, not all communities are equally protected by GI; socially vulnerable communities, with high proportions of racial and ethnic minorities and residents living in poverty, are less likely to benefit from the flood protection offered by GI [10].

Both disaster-associated and nuisance flooding due to inadequate urban stormwater infrastructure have become a regular occurrence in many lower-income communities. This is, in part, due to limited GI regulations coupled with more frequent and intense precipitation events. Despite GI providing a lower-cost approach for assisting underserved communities with increasing flood resilience compared to engineered solutions, maintenance and construction costs can sometimes prevent neighborhoods from instituting GI projects. Issues related to flood resilience are generally more easily addressed in affluent neighborhoods because of greater access to tax-based monetary solutions and other resources, while solutions for underserved communities are, in many cases, never realized [11]. Underserved communities also typically experience larger amounts of damage during flood events than other communities due to environmental degradation and inadequate infrastructure conditions [12].

Disproportionate flooding in socially vulnerable communities has unequal environmental and public health impacts, with a substantial natural hazards research literature demonstrating that those living in poverty, the elderly, minority groups, and those without access to transportation are at increased risk for adverse disaster-associated health outcomes [13]. The health impacts of flooding can include drowning, injuries, animal bites, and communicable diseases, as well as chronic diseases and mental health sequelae [14–16]. In addition, in urban areas, such as Houston, TX, which is at high risk for flooding and lacks zoning controls over land use and urban development [17], communities may also be vulnerable to environmental contamination from nearby industry or transportation infrastructure during floods, which can exacerbate chronic and acute health concerns [18,19]. Disproportionate exposure to environmental pollutants mobilized by floods among poor and minority residents of Houston was demonstrated following Hurricane Harvey in several studies [20,21]. Research has shown that minorities are more likely to perceive greater exposure to poorer environmental conditions, suffer more environmental-related health problems, and question whether public health agencies deal with environmental problems in their neighborhoods in an equitable or effective way [22].

While green infrastructure planning has been demonstrated to mitigate these negative environmental and public health impacts, rigorous evaluation of the efficacy of such plans requires further research attention. Several landscape performance tools were developed recently to quantitatively demonstrate the environmental, social, and economic benefits of built or planned projects [23]. Landscape performance can be defined as the degree of effectiveness with which the functions provided by different dimensions or components of a landscape achieve the expected goals and contribute to sustainability [23]. Examples of benefits quantified from existing landscape performance measures include carbon reduction, water quality increase, energy production, increased access to food, and increased green space for recreation or habitats [24]. To evaluate measures related to infrastructure changes, the Landscape Architecture Foundation (LAF) has compiled a series of performance tools that measure the effectiveness with which designed/planned solutions fulfill their intended purpose and help assess proposed community conditions. The performance toolkit offers a broad range of models to analyze the social, hydrologic, and economic impacts of designs and plans for adaptive resource management that can accommodate unforeseen factors affecting a landscape's overall performance. Because a majority of these calculators utilize area inputs that feed into formulae/algorithms for impact outputs, they are easily applied to community designs to examine the current and proposed performance of structural and non-structural infrastructure.

By utilizing landscape performance tools, several recent studies have reported the long-term hydrologic and economic benefits of increased GI [23,24], with the economic rationale of GI emerging as an essential component of flood-prevention strategies [25]. For example, the Center for Neighborhood Technology's (CNT) National Stormwater Management Calculator, also known as the National Green Values Calculator (GVC), is a tool that was developed to compare the costs, benefits, and performance of GI to conventional stormwater management practices [26,27]. Tools for assessing the impacts of GI are rapidly being developed and tested to quantify the flood mitigation effectiveness of GI and to assess plan effectiveness. For instance, the EPA's National Stormwater Calculator evaluates measures similar to the GVC, but only on sites 12 acres in size or smaller. Other tools, such as the Long-Term Hydrologic Impact Assessment (L-THIA), estimate the average annual runoff and pollutant loads for land-use configurations [28], while the Coastal Resilience Center's Economics of Coastal Adaptation application explores current and future flood risks and compares the cost-effectiveness of nature-based and engineered solutions to reduce risks [29].

In tandem with the growing number of models, researchers and practitioners are increasingly applying these tools to evaluate the potential impacts of GI within plans, policies, and designs. The economic benefits of using GI for flood mitigation have been repeatedly demonstrated; GI's economic benefits exceed the economic losses from flooding [30] and are greater than the costs of using only engineered infrastructure [31,32], or of stormwater utility fees [33]. GI can reduce stormwater runoff volumes, decrease the amount of the impervious surface, delay peak discharges, assist in the prevention of pollution, and help recharge groundwater [34], potentially protecting the health and wellbeing of communities impacted by rapid development industrial exposures. While this evidence is important, several gaps remain. Due to the growing number of assessment tools, selecting the right one for a specific evaluation of GI can be difficult. Further, the potential of combining multiple GI performance-related tools has not yet been widely explored. Because most landscape performance tools seek to model a single impact of design (e.g., economic, social, or hydrologic) using an individual impact calculator, the application of multiple tools simultaneously across a single site is nearly non-existent in either research or practice. The ability to combine multiple performance tools for the assessment of a single site will allow for a better understanding of these interrelated issues. This paper presents a framework for combining multiple landscape performance models to evaluate GI impacts on both flood mitigation and pollutant transfer during flooding events using a participatory planning process for Sunnyside, Houston, TX, USA, which is a neighborhood in Houston (Figure 1).

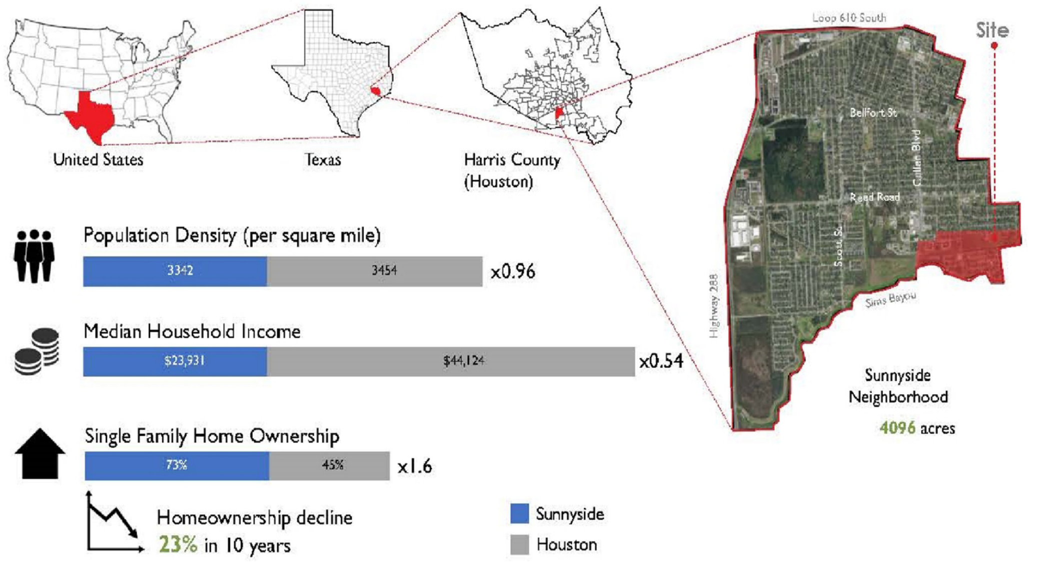

Figure 1. Location and profile of the site under investigation.

This paper both discusses this framework, applies it, then offers possible impacts of its application moving forward. As part of the framework development, we modeled and evaluated the performance of structural and non-structural infrastructure solutions used to mitigate the impacts of hurricanes/floods on pollutant release and exposure. Then, low impact design (LID) was combined with participatory research so that community members were empowered as partners in the data collection, analysis, planning, and implementation process to ensure that local concerns were addressed effectively and efficiently. The following sections detail our approach to the application site's master plan, how the master plan was developed, and then give the results of evaluating the outputs of each model regarding the master plan's impact on both flooding and contamination reduction. Finally, a discussion on policy recommendations, future research, and the limitations of the study is presented.

2. Case Study

2.1. Study Area and Population

The City of Houston is frequently impacted by flooding associated with both coastal storms and inland precipitation [35]. Major flood events, such as Tropical Storm Alison (2001), Hurricane Ike (2008), Memorial Day flooding (2015), Tax Day (April 15) flooding (2016), Hurricane Harvey (2017), and Tropical Storm Imelda (2019) have led the City of Houston to one the largest numbers of flood-related fatalities in the United States [12,36]. The neighborhood of Sunnyside, the city's oldest African American neighborhood, is located in South Houston, adjacent to Sims Bayou [37]. Sunnyside is frequently impacted by flooding due to aging and inadequate stormwater infrastructure and drainage. Originally platted as a racially segregated subdivision in 1915, Sunnyside established a water district and a volunteer fire department in the 1940s and slowly developed as a low-density, single-family home community that was annexed by the City of Houston in 1956 [38]. The population of Sunnyside is currently 21,158 living in an area of 4096 acres; population loss since 2000 has decreased its population density to 3342 people per square mile [39]. Ninety percent of the population is African American, with a growing proportion of Hispanic residents (8%). Twenty-two percent of the total land area in the neighborhood is considered vacant [40]. Homeownership in Sunnyside has declined by 23% since 2000, contributing to the gradual disinvestment in the neighborhood; Sunnyside also has 346 tax-delinquent parcels [37]. According to the 2016 Neighborhood Plan, Sunnyside's median household income was lower than the City of Houston's, with 54% of Sunnyside's residents having less than USD 25,000 annual household income. The City of Houston's Community Health Profile (Houston Department of Health and Human Services 2014) shows that the neighborhood faces a violent crime rate (22.7 per 1000 population annually) that is almost twice that of the City of Houston, while the City of Houston's Department of Health and Human Services finds that within one mile of Sunnyside, there are eight facilities that participate in toxic release inventory (TRI) reporting; three large-quantity generators (LQG) of hazardous waste; two major air pollutant dischargers; and one facility involved in the treatment, storage, or disposal of hazardous waste.

The Sunnyside–Greater Hobby area ranks among the top three super neighborhoods in terms of the percentage of people having fair or poor health and barriers to accessing care [41]. A 2012 needs assessment conducted in Sunnyside found that the primary barriers to receiving health information were a lack of knowledge about what is available or not understanding the information (37.1%); inability to pay for services (32.3%); and inability to get to a clinic, hospital, or library to access information (13.7%) [42]. Compared to Harris County, Texas, where Houston is located, health indicators reported by the Texas Department of State Health Services are significantly worse for Sunnyside's African American residents, including lifetime asthma prevalence (17.5% versus 8.3%), current asthma prevalence among children (14.3% versus 8.9%), and asthma hospitalization rates among children age 0–17 (34.2/10,000 people versus 10.9/10,000). The mean life expectancy of Sunnyside from 2010 to 2015 was 70.2 years, which is around 8 years lower than the 2014 estimates for Harris County and Texas [43].

2.2. Community Issues

The primary barriers to the implementation of GI in underserved neighborhoods like Sunnyside are questions about efficacy, aesthetics, and, perhaps most importantly, cost [44]. While socially vulnerable residents may broadly support the implementation of GI in their neighborhoods [45], the high initial costs and ongoing financial obligations for maintenance are reported as barriers to the implementation of GI projects. Neighborhoods with higher poverty rates and larger percentages of African American and Hispanic residents are relatively underexposed to green spaces compared to their wealthier, whiter neighbors [46]. Parks that minority and low-income populations do have access to have been shown to have higher congestion [47], more basketball courts but fewer trails and other ecological features [48], and occupy neighborhoods receiving low amounts of ecosystem services due to decreased tree density, leaf area index, tree and shrub cover, and tree and shrub diversity [49]. Minority communities also typically experience increased exposure to natural hazards and a constrained ability to prepare for and recover from disasters [50,51].

Sunnyside, the application case site for this research, is a community with a rich culture and shared values but has also suffered from a myriad of problems including inadequate infrastructure investment, limited access to economic resources and affordable housing, low-quality open spaces and transit options, public safety, vacant lands, and increasing risks to flooding hazards. A large proportion of the neighborhood's parcels are designated as being in the 100- and 500-year floodplains, with frequent ponding issues after heavy rainfall or storm events (Figure 2). For example, the Draft Action Plan for Disaster Recovery [52] estimated USD 545 million of housing and infrastructure damages in Sunnyside from the 2015 Memorial Day and Halloween storms combined. This plan shows that flooding coincided with the open ditch locations in Sunnyside. Impervious surfaces and inefficient placement of existing parks make water absorption and filtration difficult. The combination of open ditches and vacant lands exacerbates water ponding problems while making these areas susceptible to the disposal of waste, broken furniture, discarded appliances, and debris.

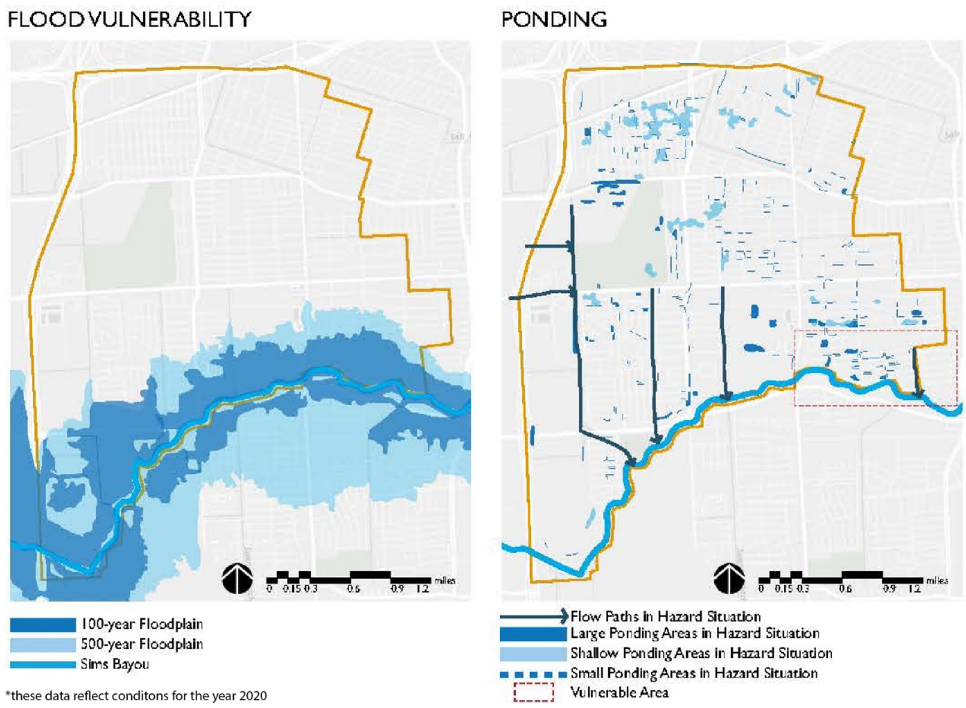

Figure 2. Floodplain and stormwater ponding areas in Sunnyside, Houston, TX, USA: 2020.

3. Methods

3.1. Overview of Approach

To serve as a model for future development within the neighborhood, a 202-acre site in the southeast portion of the Sunnyside neighborhood was selected as the design and research study area based on community preferences. The methodology for this research was a three-step process involving a myriad of tasks within each step. First, the authors utilized participatory sessions to identify existing problems and challenges, which were revealed by neighborhood residents, stakeholders, and local organizations. Then, the development, visualization, and production of the master plan were led by the authors of this manuscript through a service-learning process, in conjunction with community members and a planning-based outreach program known as Texas Target Communities, a unit with nearly 30 years of experience in developing plans for neighborhoods. After finalizing the master plan, to project its probable impacts, the researchers utilized a series of proven spatial performance models and tools to quantify its effects. The sections below further outline the procedures utilized within these steps to fully develop the engaged master plan and apply the performance tools and models to the plan once it was developed.

3.2. Problem Identification

Problem identification was conducted through an inventory and analysis of existing conditions using comprehensive mapping and visualizations and community engagement activities. Geospatial data were gathered regarding land use and land cover, park and vegetation density, transportation, and other urban amenities. Maps were produced to show the spatial distributions of physical environmental features and access to opportunities from various blocks within the site. For example, circular buffers were created using ArcGIS Pro to generate service areas of bus stops and parks, which displayed areas within the study area that lacked critical infrastructure.

In addition to geospatial assessments of environmental and infrastructural conditions, we directly engaged with community members and interested stakeholders to ensure that the direction of this research was partly led by the desires and local knowledge provided during these events. The initial engagement consisted of a tour of the site led by 1 community resident, 3 leaders of a local organization known as Charity Productions, 28 undergraduate students, and 4 university professors. Charity Productions linked professors and professionals with underserved and marginalized communities to help solve neighborhood issues through engagement. The initial session provided residents the opportunity to voice concerns about community issues (environmental, health, education, services) and identify the spatial locations of the primary problem areas of environmental degradation, which was accomplished through a guided tour of the community. Subsequent follow-up discussions allowed the researchers to present their inventory and analysis results to residents to ground truth these results. Feedback from the community on the inventory and analysis provided valuable insights related to unknown conditions and provided a list of initial ideas to consider when developing the master plan.

Through this process, we identified critical environmental and infrastructural problems to be targeted in this engaged research: (a) major concentrations of vacant parcels, (b) frequently affected by flooding and stormwater ponding, (c) lack of public amenities, and (d) a high need for increased GI. For example, only 18% of the area was within a quarter-mile radius of a bus stop. There were no existing sidewalks and the open ditches along the streets created a sanitary hazard. Around 9% of the site was considered underutilized space with no community use. The existing tree canopy covered 36% of the site, but there was no park facility. A majority of the site's parcels were vacant or abandoned (Figure 3). Using the identified issues, goals were set for the subsequent master planning, including repurposing vacant land, providing green infrastructure for stormwater capture and carbon sequestration, as well as reducing non-point pollutants.

Figure 3. The site's spatial characteristics and conditions in Sunnyside, Houston, TX, USA.

3.3. Engaged Master Planning

A master plan for the community was developed through a continued series of community engagement sessions. These four sessions took place once every two months over 8 months. The first meeting focused on informing residents about how the identified community concerns might be alleviated through infrastructure and land-use changes while incorporating resident feedback. Based on the discussions, students produced conceptual drawings with preliminary design ideas, especially related to the characteristics and placement of green infrastructure. The second meeting allowed students to interact with local residents and high school students and present initial analysis findings and drawings. After this meeting, students developed various scenarios of land-use change and produced transportation, green infrastructure, and pedestrian amenities plans. The third meeting was a presentation of different design scenarios to local organization leaders and community representatives. A feedback loop was incorporated in a follow-up meeting between community members and the design team, which allowed for the presentation of design scenarios and critiques by stakeholders and community members. Feedback from each design scenario was used to inform a final master plan, a condensed version of relevant ideas pulled from each scenario guided by landscape performance measures. During the final meeting, the final master plan was presented to leaders of Charity Production, residents, and the engaged high school students.

Overall, using an evidence-based approach focused on LID, which is a design and planning method to help manage stormwater and environmental health threats as close to their source as possible, a master plan that included a vision for future community design and growth, land-use changes and development options, infrastructure improvements, and open space planning was developed with the overarching goal of reducing the environmental impact and public health risk of exposure to hazardous substances mobilized during environmental disaster events. Specifically, through LID and engaged planning, vacant land reuse was maximized to provide space for ecological, hydrological, and other non-traditional land uses. Vacant land was repurposed as a catalyst for reconnecting natural systems; like connective social tissue, GI provides flood attenuation, as well as other ecosystem services to areas undergoing transformation.

3.4. Landscape Performance Evaluation

This research used a multi-combinational approach to analyze the conditions in Sunnyside by applying a mixture of highly used performance models. To conduct the analysis of the developed participatory master plan, three GI-related performance tools were applied to the master plan: the Value of Green Infrastructure (VGI): A Guide to Recognizing Its Economic, Environmental and Social Benefits Tool; the GVC; and the L-THIA Low Impact Development Spreadsheet. A description of each tool and justification of its utilization is presented below.

The Value of Green Infrastructure (VGI): A Guide to Recognizing Its Economic, Environmental and Social Benefits was developed to assess the economic benefits provided by GI. It provides formulae for quantifying both stormwater reduction amounts and an economic valuation of the reduction in stormwater due to GI provisions. A complete overview of the formulae and needed measures for the tool can be found here: https://cnt.org/publications/the-value-of-green-infrastructure-a-guide-to-recognizing-its-economic-environmental-and (accessed on 2 February 2022). The VGI tool helps decision makers to understand, quantify, and assign economic value to GI practices and investments [26,27]. It has been heavily used in both research and practice to estimate water, energy, air quality, and climate change mitigation benefits for green roofs, permeable pavement, and rainwater harvesting [53].

Another CNT tool, namely, the GVC, has been used to assess the effectiveness of stormwater management practices on water quality and hydrology [54], build adaptive capacity for flood proofing urban areas [46], predict green roof runoff capture [55], assess GI impacts in new housing developments [56], and evaluate stormwater runoff storage for urban community gardens [57]. The GVC calculates the volume of runoff based on inputted land use percentages. The valuation of the impact of GI on infiltration rates, evapotranspiration amounts, and stormwater runoff reuse is calculated by modeling the ability of each type of GI utilized to capture runoff [58,59]. Both construction and maintenance costs for each type of GI utilized in the design/plan are estimated, providing a total life-cycle cost for a given project at 5-, 10-, 20-, 30-, 50-, and 100-year periods. The formulae inherent to the tool and the list of input and out variables can be found here: https://cnt.org/tools/green-values-calculator (accessed on 2 February 2022).

The L-THIA model is an urban growth analysis tool that estimates the long-term runoff and non-point source pollution impacts of different land use development scenarios. It provides the estimated long-term average annual runoff, rather than only extreme events, based on long-term climate, soil, land-use, and curve number (CV) conditions for specified state and county locations in the United States. It also generates estimates of 13 types of non-point-source pollution loadings to water bodies (e.g., nitrogen, phosphorous, suspended particulates) based on land-use changes. Land-use classes that are used as input variables for the model include commercial, industrial, high-density residential, low-density residential, water/wetlands, grass/pasture, agriculture, and forest. The model has been used to track land-use change in watersheds for historical land-use scenarios [60,61], identify areas sensitive to non-point-source pollution, and evaluate land-use development for non-point-source pollution management [62]. The full spreadsheet for data input needs and formulae for the tool can be found here: https://engineering.purdue.edu/~lthia/ (accessed on 2 February 2022).

4. Results

4.1. Master Plan Output

The final master plan for Sunnyside focuses on green infrastructure for ecological benefits but also achieves multifold co-benefits, including housing and community support and employment generation (Figure 4). The developed plan includes a new green infrastructure network, which is a connected set of open spaces to improve urban stormwater management and water quality. For example, Sunbeam St, acting as an eco-boulevard, traversed the center of the site connecting the area to the primary arterial roads to the west and east. Pedestrian trails were also interwoven through the green infrastructure network, increasing pedestrian access to adjacent land uses and facilities.

Figure 4. Participatory master plan and schematics developed for Sunnyside, Houston, TX, USA.

4.2. Master Plan Overall Performance

This section presents the outputs from each performance calculator utilized for the Sunnyside Neighborhood Master Plan. Table 1 shows the percentage of GI types within the neighborhood, comparing existing conditions with the master plan's design. For the inputs, the total percentage of and total square footage of the pervious surface area (amount of non-hardscaped landscape), the percentage of green space (the amount of non-developed area), the percentage of development area (area with buildings, streets, or impervious surface), and the square footage of green roof area (a type of green infrastructure where is vegetation planted over a waterproofing system that is installed on top of a flat or slightly sloped roof) were all calculated. The implementation of green practices in the master plan for Sunnyside increased the projected pervious surface area from 10% to 32%. The projected green space increased nearly threefold, from 9% to 26%. The master plan also added green roofs (219,978 square feet) and rain gardens (27.2 square feet).

Table 1. Green practices in Sunnyside Neighborhood Master Plan.

Site Context	Pre-Existing Lot Conditions	Post-Master-Plan Scenario
Pervious Surface (%)	10	32
Green Space (%)	9	26
Development Area (%)	41	68
Green Roofs (ft^2)	0	219,978
Rain Gardens (ft^2)	0	27.2
Pervious Surface (ft^2)	879,912	2,815,718.4

4.3. Outputs from Individual Performance Calculators

4.3.1. Benefits of Green Infrastructure (GI): The Value of Green Infrastructure (VGI Outputs)

Benefits for two types of GI were calculated in this study: green roofs and rain gardens. Some of these GI benefits were further divided into sub-service types. Calculating each GI benefit required two steps, namely, benefit quantification and benefit valuation, the product of which was the annual benefit (in USD) for each benefit sub-service type. The total annual benefit of reducing stormwater runoff was the summed benefits of the two types of GI (green roofs and rain gardens), which, in this case, was USD 12,921.16. Following the same calculation process, the annual benefits of reducing energy, improving air quality, and reducing atmospheric CO_2 in the study area were, respectively, USD 20,200.821, USD 1663.89, and USD 2336.39. The total annual benefit of the two types of GI proposed in Sunnyside was USD 37,122.261 (Table 2).

Table 2. Design impact outputs from various landscape performance calculators.

Methods	Green Infrastructure Benefits	Post-Master-Plan Scenario	Annual Benefit (USD)
VGI output	Reduce stormwater runoff (annual stormwater retention) (gal)	2,499,258.19	12,921.16
	• Green roofs	2,315,052.865	
	• Rain gardens	184,205.329	
	Reduce energy (annual electricity saving) (kWh)	210,644.64	20,200.821
	• Green roofs	210,357.65	
	• Rain gardens	286.99	
	Improve air quality (annual NO_2 benefit) (lbs)	498.17	1663.89
	• Green roofs	498.17	
	Reduce atmospheric CO_2 (annual climate benefit) (lbs)	309,045.988	2336.39
	• Green roofs	309,045.988	
	Construction costs (USD)	26,357,902	
GVC output	• Conventional development	18,200,566	
	• Green infrastructure development	8,157,336	
	Annual maintenance costs (USD)	572,668	
	• Conventional development	315,597	
	• Green infrastructure development	257,071	
	Average annual rainfall		
GVC output	• Total runoff (in)	20	
	• Total runoff volume (ft3)	14,661,951	
	• Cumulative abstractions (in)	1.58	
	90% storm		
	• Total runoff (in)	0.34	
	• Total runoff volume (ft3)	252,577	
	• Cumulative abstractions (in)	0.61	
	Curve number (CN)	85	
	Initial abstractions (in)	0.34	
	Non-Point-Source Pollutant Results	**Post-Master-Plan Scenario**	**Post-Plan Change**
L-THIA	• Nitrogen (lbs)	271	−94.95
	• Phosphorous (lbs)	69.04	−11.98
	• Suspended solids (lbs)	9452	−8109
	• Lead (lbs)	1.47	−2.53
	• Copper (lbs)	1.48	−2.53
	• Zinc (lbs)	27.02	−43.99
	• Cadmium (lbs)	0.17	−0.41
	• Chromium (lbs)	1.13	−0.88
	• Nickel (lbs)	1.50	−0.50
	• Biological oxygen demand (BOD) (lbs)	4338	274.32
	• Chemical oxygen demand (COD) (lbs)	17,953	4747
	• Oil and grease (lbs)	1285	415
	• Fecal coliform (millions of coliform)	8705	−4093

4.3.2. Green Values National Stormwater Calculator (GVC) Outputs

Construction costs in Sunnyside for the final designed master plan developed through the previously described engagement process totaled USD 26,357,902. The total construction cost for conventional development in the Sunnyside site would be USD 18,200,566, with an additional USD 8,157,336 of the projected total construction going towards GI. Since the GVC defines conventional development as development with no GI, the GI costs were calculated as an additional expense, although it is still typically cheaper than comparable engineered infrastructure implementation. Total annual maintenance costs for the proposed plan in Sunnyside were USD 572,668. While the added GI makes initial construction more expensive than conventional development in the construction phase, savings are realized in the life-cycle costs. The maintenance cost for conventional development was USD 315,597, while the projected total annual maintenance cost for GI was USD 257,071.

Compared to conventional approaches, the green practices tested in this analysis will decrease the total average annual rainfall runoff (and runoff volume) by 3% (from 20.69 in. and 15,169,032 ft^3 to 20 in. and 14,661,951 ft^3). For a 100-year storm event, the difference was much more dramatic, with the green practices reducing runoff (and runoff volume) by 37% (from 0.55 in. and 401,341 ft^3 to 0.34 in. and 252,577 ft^3) when compared to conventional development without GI (Table 2).

4.3.3. Non-Point-Source Pollution Impact of the Master Plan (L-THIA Outputs)

Non-point-source pollution impacts comparisons between the pre- and post-master-plan scenarios were also calculated in this study. Thirteen types of non-point sources of pollutant loadings to water bodies (e.g., nitrogen, phosphorus, suspended solids) were estimated from the L-THIA model based on the land-use changes. The results showed that 10 of the 13 types of non-point-source pollution were reduced after the master plan implementation, reducing the amount of non-point-source pollutant loading to water bodies across the Sunnyside site (Table 2).

5. Discussion

The City of Houston is exceptionally vulnerable to flood disaster events due to its impervious surfaces, low-lying location along the coast, and high density of industrial facilities. The potential impacts of flooding on human health are exacerbated by a lack of zoning to restrict certain land-use types in close proximity to residential areas. Racial and ethnic minority, economically disadvantaged, disabled, and elderly populations are disproportionately affected by disaster events [63,64] and adverse health outcomes [13]. Although the risks associated with flooding could be reduced by addressing poor infrastructure conditions and environmental degradation [12], underserved communities often lack the financial and human capital required to implement proposed improvements [11]. Therefore, a growing need exists for sustainable flood risk reduction strategies that are attainable by resource-limited urban communities.

As noted, the Sunnyside neighborhood is home to a predominantly African American population that is challenged by excess rates of poverty and unemployment [43] and is susceptible to flood-related damage [65]. The Sunnyside Neighborhood Master Plan was developed with the support of community members and tailored to address the concerns and interests of Sunnyside residents. If the GI proposed is implemented in its entirety, the master plan would reduce the risk of flooding by increasing the site's stormwater capture and control capacity by 17.8% compared to the conventional approach alone. Specifically, this would be achieved through a 15.4% reduction in impermeable surface area to facilitate stormwater infiltration, a 22% increase in green space to enhance evapotranspiration and infiltration, and the development of rain gardens to store and reuse an estimated 37% of stormwater runoff.

In addition to direct public health improvement opportunities, this has the potential benefit of long-term economic improvement conferred by reducing childhood exposure to environmental contaminants that are known to induce developmental deficits and impair future productivity. Preliminary research suggests that exposure to lead through the consumption of contaminated tap water may be more common among Houston households than is presently recognized [66]. Children exposed to lead are less likely to achieve high-school-level educational attainment, leading to lower earning potential and vulnerability to future financial instability [67]. The proposed master plan is projected to achieve a significant reduction in lead pollution from non-point sources compared to conventional approaches in the absence of GI. Although the master plan alone would not eliminate all lead in the environment, any reduction in childhood lead exposure is beneficial, as there is no threshold of safe lead exposure [68].

The economic benefit of the proposed GI will pay itself off in 33.5 years in indirect benefits and will cover 30% of GI construction costs in one 100-year life cycle. Simultaneously, the design can capture 81,057 ft^3 of runoff, creating USD 243,856 in annual green benefits (including reduced air pollutants (USD 133), carbon dioxide sequestration (USD 88), groundwater replenishment (USD 1231), reduced energy use (USD 39,596), reduced treatment benefits (USD 683), and compensatory value of trees (USD 202,125)). Compared to conventional approaches (without the addition of GI), the green practices tested in this analysis decreased the total average annual rainfall runoff (and runoff volume) by 3%; for a 90% storm event, the green practices reduced runoff (and runoff volume) by 37% compared to conventional development without GI. While the solutions proposed can benefit the neighborhood in the long term, short-term cost burdens include the installation and maintenance expenses, which can create additional burdens for already marginalized communities. It is important to note, however, that the present study does not address opportunity costs that could be incurred as a result of inaction nor does it include potential economic advancements due to job creation and enhanced property values due to capital improvements.

In addition to the aforementioned benefits, the Sunnyside Neighborhood Master Plan is likely to produce indirect improvements in the mental and physical health of Sunnyside residents. Reductions in stormwater runoff may reduce the incidence of exposure-associated health conditions or the exacerbation of existing conditions, such as long-term mold in homes, already excess rates of asthma, and older homes. Relatedly, several heavy metals, such as lead and chromium, have deleterious health outcomes after exposure. Although no longer used in gasoline in the United States, lead is used in petrol-based materials, pesticides, and batteries. Chromium is used in chrome plating, petroleum refining, electroplating industries, leather tanning, textile manufacturing, and pulp processing units. Any future findings could be compared to the Texas Commission on Environmental Quality background concentrations of health metals in sediments to assess for changes.

6. Conclusions

This study presented a novel methodological framework for integrating multiple landscape performance tools to quantify the multifold benefits of GI-focused community participatory planning. All three tools presented were integrated in a unique manner to model the benefits of green infrastructure and LID practices by taking into consideration the location-specific conditions and the types of land use and GI interventions proposed. The coupling of these three tools provided a comprehensive method to assess the economic, hydrologic, and hazardous substance level impacts of the proposed green infrastructure provision. While most research only utilizes one tool, this study linked multiple performance models for a singular purpose. Further, projected pollutant load decrease was incorporated in this research, which is a rare evaluation metric for current landscape performance studies.

The results also revealed the strengths and weaknesses of each tool. Compared to the other tools, the VGI offers a comprehensive guide to the estimation of the regulating, supporting, and cultural services associated with the most common types of GI [56]. With detailed explanations of the calculating process, this tool emphasized evidence-based metrics from diverse research reports, affording a deeper understanding of how design circumstances and contextual information influence valuation outcomes. The GVC provides similar functions, with a unique emphasis on comparing and contrasting the costs and benefits of conventional development versus developmental scenarios with GI improvements. The full life-cycle analysis is another strength. As the environmental and social benefits of GI take time to unfold, a clear valuation of the life-cycle benefits can prevent decision making that achieves immediate benefits at the expense of long-term costs. The L-THIA tool complements the others by quantifying the heavy metal and nutrition loads [57], which are of particular significance to studying environmental equity related to contamination exposure.

These tools can, however, be challenging for residents and non-academics to learn quickly. However, our findings showed that using the performance tools in participatory planning can facilitate collective forward-looking decision making. When involving stakeholders with diverse interests, the planning process is dependent on the values and social-cultural assets of the group [58]. As the literature has demonstrated, the values of green space and ecosystem services have not been well captured in conventional community planning and governance [69,70]. Evidence-based valuation tools presented in this paper allowed for the consolidation of complex benefits and comparison of GI in different planning and design scenarios and empowered the members of the community to make informed decisions. The community members could, therefore, engage in a process of trial and error to assess the outcomes of design interventions as a way to negotiate the costs and gains and develop a shared vision.

Finally, there are some limitations to using landscape performance models, namely, in their predictive capabilities. Predictive methods are another source of numerical information. These models and calculations can be used to determine likely outcomes in situations when actual performance cannot be measured. For example, direct measurement of stormwater runoff reduction provided by GI can be extremely complicated, but predictive models have been developed to estimate this value. However, predictive models and methods are less desirable than actual measurements because they do not consider all of the nuances of a particular built or natural landscape. However, developing methods for assessing predicted outcomes can allow for a more complete picture of benefits than would be possible through direct measurement alone.

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