https://doi.org/10.15302/J-LAF-1-040031

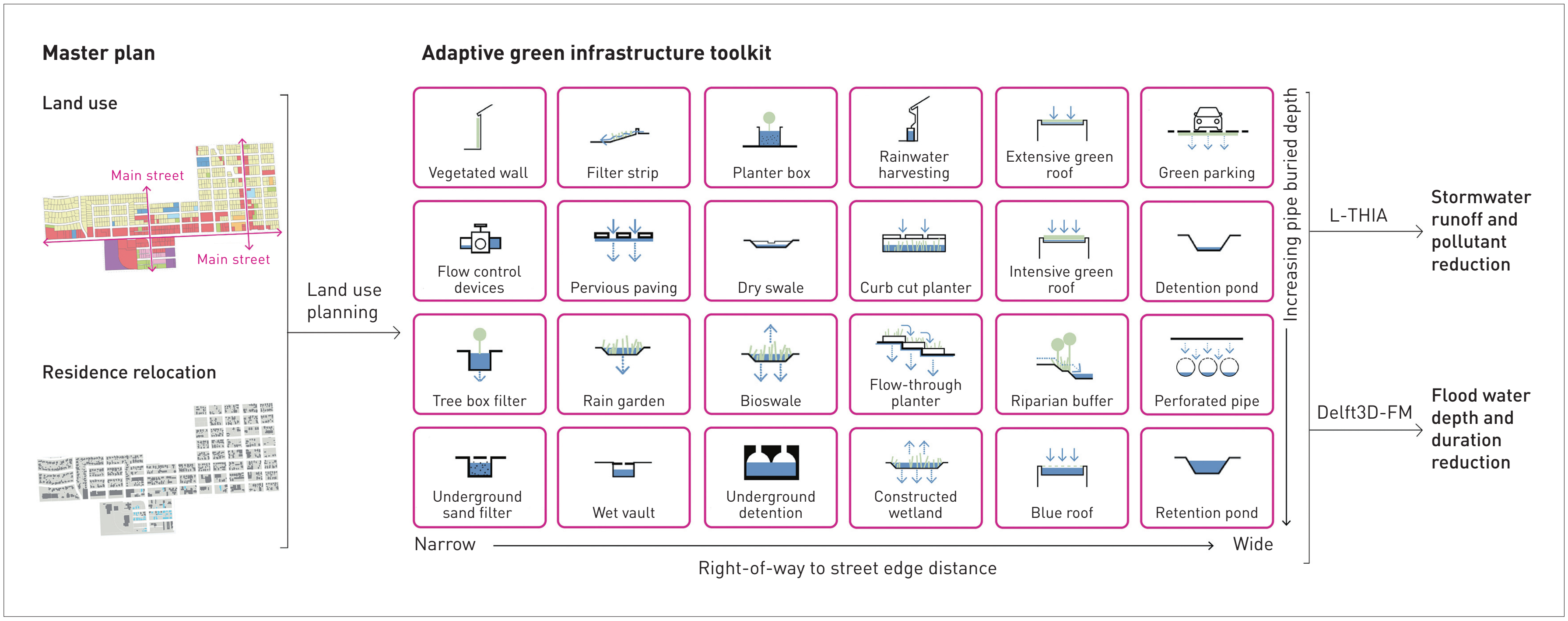
An Adaptive Toolkit for Projecting the Impact of Green Infrastructure Provisions on Stormwater Runoff and Pollutant Load —A Case Study on the City of Galena Park, Texas, USA

Rui ZHU[1,*], Galen NEWMAN[1], Sunghoon HAN[2], James KAIHATU[2], Tianyi WANG[1]

1 Department of Landscape Architecture and Urban Planning, Texas A&M University, College Station, TX 77843, USA
2 Zachry Department of Civil and Environmental Engineering, Texas A&M University, College Station, TX 77843, USA

*CORRESPONDING AUTHOR
Address: Texas A&M University, 3137 TAMU, College Station, TX 77843, USA
Email: zr1991@tamu.edu

GRAPHICAL ABSTRACT



HIGHLIGHTS

- The adaptive green infrastructure toolkit can help reduce flood vulnerability and exposure to industrial contaminants in urban areas
- Integration of the L-THIA and Delft3D-FM models provides a dynamic assessment of stormwater runoff reduction and pollutant mitigation
- The toolkit can be tailored by both on-ground spatial size and underground depth of obstruction
- The toolkit can assist master planning to significantly reduce stormwater runoff and non-point source pollutants

KEYWORDS

Stormwater Runoff;
Pollutant Load;
Public Health;
Adaptive Green Infrastructure Toolkit;
Delft3D-FM;
L-THIA Model

RECEIVED DATE

2022-08-16

ABSTRACT

The implementation of green infrastructure in retrofit projects to reduce flooding and pollution is a significant challenge in space-constrained and overly developed communities which also have complex underground utility systems. To overcome this challenge, the authors have developed an adaptive green infrastructure toolkit that can be tailored by both on-ground spatial size and underground depth of obstruction. This study aims to assess the effectiveness of this toolkit in mitigating flooding and non-point source pollutants by demonstrating the case of the city of Galena Park, Texas, USA, which has suffered from severe flooding as well as on-ground and underground space constraint issues. We first applied the toolkit to create a master plan for Galena Park and evaluated the effect of the plan by using the Delft3D-FM (Flexible Mesh) flood model alongside the Long-Term Hydrologic Impact Assessment (L-THIA) model. The results demonstrate progressive reductions in stormwater runoff and NPS pollutants across different phases. These findings highlight the toolkit's effectiveness in improving water management and pollution control, providing valuable empirical evidences for similar communities facing similar challenges.

EDITED BY Ying WANG, Tina TIAN

1 Project Description

1.1 Background

Extreme weather events have become more frequent in recent years[1]. The effects of climate change make it more likely that metropolitan areas with long histories of being polluted by land-based industries will be subject to more devastating and more frequent flooding in the coming years[2]. As one of the world's largest petrochemical complexes, Harris County, TX, USA faces public health concerns from the transfer of hazardous substances to increasingly severe flooding[3]. Heavy metals, such as lead (Pb), zinc (Zn), and copper (Cu), are common in urban soils due to industrial operations. Toxic heavy metals discharged from industrial land uses can be transmitted through flood water to nearby residential areas and deposited in soil[4]. Flooding brought by extreme weather has several detrimental effects on public health, including injury, exposure to germs, and stress. The transfer of harmful substances through floodwater aggravates this situation by increasing the chances of short-term illnesses, such as rashes, burns, and fevers, as well as long-term diseases including disability, poverty-related diseases and mental disease[5][6]. Green infrastructure (GI) has been proven to be an effective solution to reducing flooding, pollutant loads, and the amount of hazardous substance transferal during flood events. However, it is commonly believed that incorporating green infrastructure features often necessitates ample land area to facilitate the infiltration of stormwater into the soil[7]. In fully developed areas with limited on-ground undeveloped spaces and complex underground utilities (like pipes and cables that transport electricity, natural gas, water, sewage, and telecommunications), these problems might be more difficult to alleviate than in less developed areas.

To overcome these challenges, we have developed an adaptive GI toolkit that employs a combination of flood-proofing tools and pollution-relief techniques and can be tailored by both on-ground spatial size and underground depth of obstruction. To put the toolkit to the test and assess its effectiveness, we selected a community retrofit project in Galena Park in Harris County as a case study. We meticulously crafted and implemented a master plan for the community, incorporating the various elements of the adaptive GI toolkit and sought to evaluate how well the adaptive GI toolkit could mitigate stormwater runoff and non-point source (NPS) pollutants (including nitrogen, phosphorus, suspended solids, lead, copper, zinc, cadmium, chromium, nickel, BOD, COD, and greases).

While the use of landscape performance tools which seek to quantify the impact of planning and design on cities has rapidly increased in recent years, little research has coupled their plans with sophisticated modeling techniques to simultaneously evaluate

1. Galena Park has a long history of industrialization and is now home to multiple petrochemical and aerospace industries.

1 © Tianyi Wang

the effectiveness of design on rainfall-induced inland flooding and hurricane-induced storm surge. Most studies on flooding for urban planning have focused only on assessing flooding impacts under specific scenarios that are relatively static, such as assessing the generation of average daily flow rates and water levels. But these studies often overlook the potential for flooding events occurring at smaller time scales, such as hourly intervals, which are crucial for capturing the dynamic nature of flood events, including the effects of storm surges propelled by hurricanes[8]. However, in low-lying coastal areas such as Harris County, determining the impact of compound flooding from both rainfall-induced inland flooding and hurricane-induced storm surge, as well as the level of mitigation by proposed flood reduction master plans, requires a dynamic, holistic approach to modeling.

The uniqueness of this project lies in its use of Delft3D-FM (Flexible Mesh) coupled with the Long-Term Hydrologic Impact Assessment Low Impact Development (L-THIA/LID) model to project the probable effect of the master plan on flood reduction. L-THIA/LID is a straightforward analytical tool designed for planners and natural resource managers, applicable to various locations to provide estimates of long-term effect of land-use changes on stormwater and NPS pollution.[9]~[11] It can specifically be used to simulate the impact of land use change on rainfall-induced inland flooding in the proposed master plan. This model uses Genetic-Algorithm (GA) to help automatically calibrate Curve Numbers (CNs) for directing runoff estimations. Therefore, it could calibrate surface runoff and NPS by reducing the discrepancies between the observed and simulated data based on the optimized CNs and Even Mean Concentrations (EMCs)[12]. Many researchers also utilized this tool to assess the performance of their designs. For instance, Galen Newman et al. investigated the potential effect of resilient community design on flood risk and pollutant loads[13]; Ebrahim Karimi Sangchini et al. projected the effect of land cover management scenarios on runoff volume and river pollutants at a basin scale[14]. However, L-THIA/LID does not account for the potential impact of extreme storms, but such an impact may significantly impact the hydrological processes and water flows of a site that cannot be ignored. Thus, the Delft3D-FM model was applied together to compensate for this limitation.

Delft3D-FM is able to simulate hurricane-induced storm surge flooding over smaller time scales (e.g., hours) by considering the impact of storm surge pushed ashore by hurricane winds[8]. With the help of this model, we could see how flooding may build and recede over the scale of minutes or hours as storms move through a coastal area[15]. By combining L-THIA and Delft3D-FM models, our study presents how design affects long-term average annual stormwater runoff and NPS pollutants, as well as offers a dynamic picture of the effect of any time lags between rainfall-flooding maxima and hurricane surge maxima.

1.2 Site Challenges

Galena Park, located in a highly industrialized area (Fig. 1) east of the 610 Highway in Houston, TX and north of the Houston Ship Channel in eastern Harris County, is a 3,148.8-acre city with a population of 10,740 at the 2020 census①. As early as the 1900s, Galena Park developed petroleum by taking advantage of its prime location. Today, Galena Park is home to multiple petrochemical and aerospace industries. Because of bayou proximity and its insufficient conventional drainage system, flooding has been a severe issue to the city. As a result, industrial substance transferal during storm events has also significantly increased health risks to Galena Park's population. For example, for Tropical Storm Allison in 2001[16], about 3.4% of the city area, including 28.1 acres of industrial sites, was inundated; in 2008, flooding brought by Hurricane Ike submerged about 9.2% of the city area including 67.5 acres of industrial sites[17]. Hurricane Harvey in 2017 caused devastating flooding in the city, inundating 17.3% of Galena Park including 58.3 acres of industrial land. Hurricane Harvey was also estimated to have had the most risk of NPS pollutants transfer, followed by Ike and Allison[18]. Thus, Galena Park has been and will be threatened by point and NPS pollution.

According to research, point and NPS pollution is related to injury, non-communicable disease, and nutritional disease[19]. Sharp debris and wildlife in stormwater runoff can increase physical health risks, such as fatal drowning and injuries[20]. Suspended soil carried by floods can release heavy metals, bacteria, nutrients, and pesticides directly into the environment, leading to severe environmental degradation and public health problems[21][22]. For example, lead can cause mild mental retardation and cardiovascular diseases[23]. According to Greet Schoeters et al., prolonged exposure to cadmium may raise the risk of lung cancer in adults[24]. In comparison to the rest of Harris County, Galena Park placed in the top 5 for the prevalence of pollution-related diseases across different human health categories[25].

Galena Park will continue to be threatened by severe floods over the next 30 years at least according to the Risk Factor website, indicating that flooding is likely to divert more pollutants and significantly affect public health of the city. Figure 2 shows the estimated risk of damage and pollutant transferred from five categories of hurricanes that may occur in Galena Park. The Saffir-Simpson Hurricane Wind Scale categorizes hurricanes into five categories by intensity[26]. Category 1 hurricanes may cause damage to roofs, trees, and power lines, along with storm surges and floods. Category 2 hurricanes pose a greater threat with extensive damage potential. Category 3 hurricanes, or major hurricanes, lead to risks of structural damage and increased storm surge. Category 4 hurricanes can cause severe building damage and widespread coastal and inland floods. Category 5 hurricanes, the most intense, will lead to catastrophic destruction, power outages, and devastating storm surges reaching far inland. The hurricane category data obtained from the National Hurricane Center and Central Pacific Hurricane Center were first digitized by Arc-GIS Pro. Then, the study incorporated the categorization of Galena Park's potential contamination sources, utilizing data from the Texas Commission on Environmental Quality (TCEQ) and Toxic Release Inventory (TRI) reporting facilities. Upon calculation, it was found that in the event of a Category 4 hurricane, an estimated 41% of Galena Park would be inundated, including 568.9 acres of industrial land uses, 36 TCEQ facilities, and 4 TRI facilities. Even worse, if a Category 5 hurricane strikes, the inundated area will reach 64%, including 668.2 acres of industrial sites, 57 TCEQ facilities, and 4 TRI facilities.

To mitigate the effect of flooding, GI investment is urgently needed in Galena Park. However, as with most retrofit projects, there are two challenges to installing GI in the city. One is the city's limited undeveloped properties and potential infill sites; the other is its complex underground utilities and infrastructure (e.g., power, sewer, gas lines). An extra attention needs to be taken to GI type selection so as to avoid affecting the normal operation of the existing pipelines.

Overall, the site faces problems resulted from insufficient flood infrastructure, being highly industrialized, limited developable space, and a complex underground pipe system which is inappropriately mapped. The community retrofit project commissioned by the Galena Park government was initialized in May of 2021 and the master plan was completed in December of 2022. The city is moving forward with implementing the GI provisions as they become financially feasible. The goal is to decrease flood vulnerability and improve public health by strategically implementing GI for a 209.3-acre target site in Galena Park, which is at the highest risk of both flooding and industrial contamination. We then test the impact of the proposed GI provision using the Delft3D-FM modeling techniques. Ultimately, this project hopes to 1) provide an adaptive GI improvement strategy that can be applied to other small towns in the USA and beyond with similar flooding risks and drainage issues, and 2) present a new method with which designers and researchers can test the probable impact of proposed changes at city and community scales.

2 Design Concept

Application of the adaptive GI toolkit and the relocation of residential areas with high flood-related risk are major strategies

① The data is sourced from 2020 Census by the United States Census Bureau.

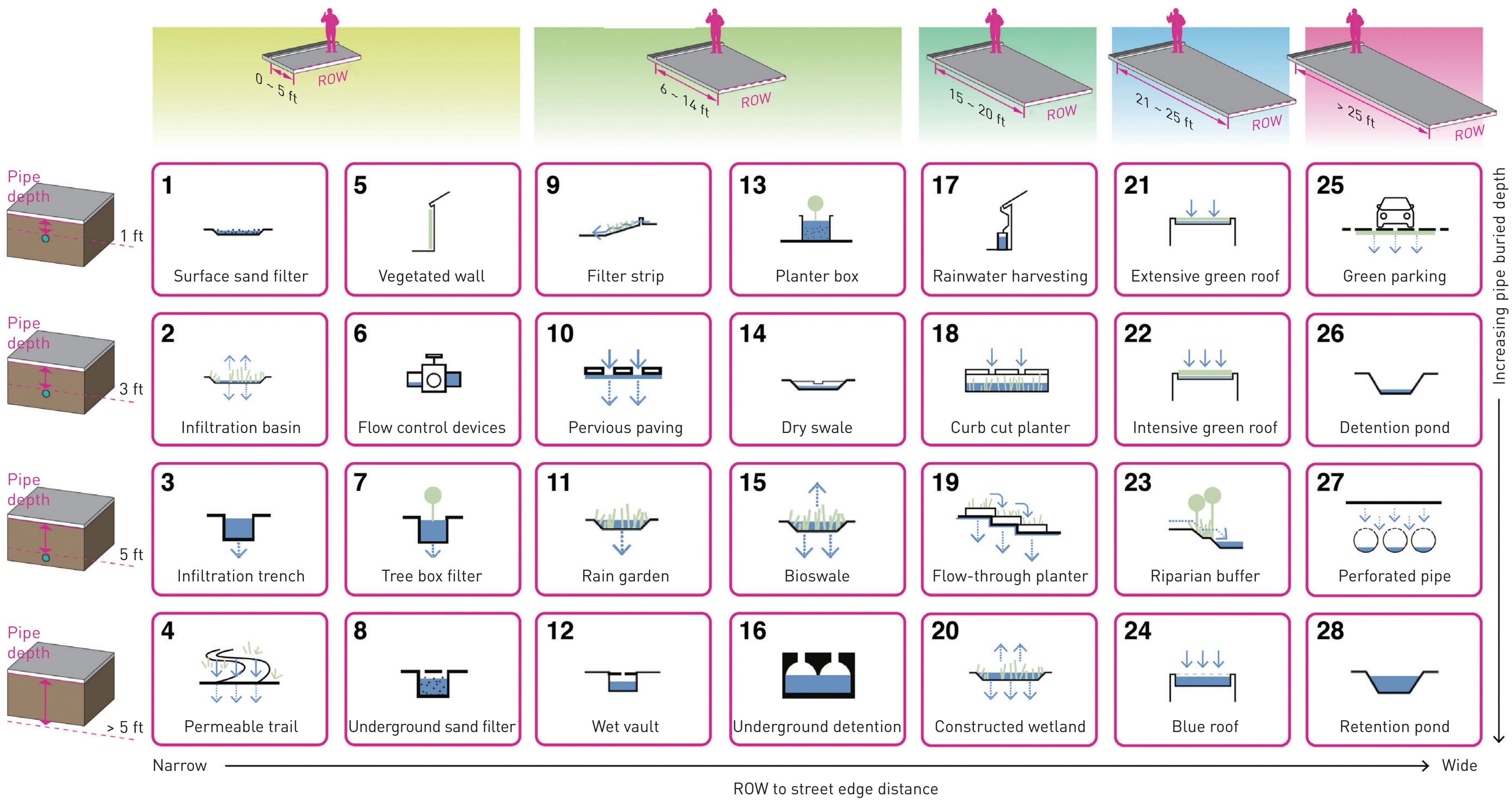
2. Estimation of the risk of damage and pollutant transferred from five categories of hurricanes in Galena Park, as it may suffer from severe risk of flooding over the next 30 years and beyond.

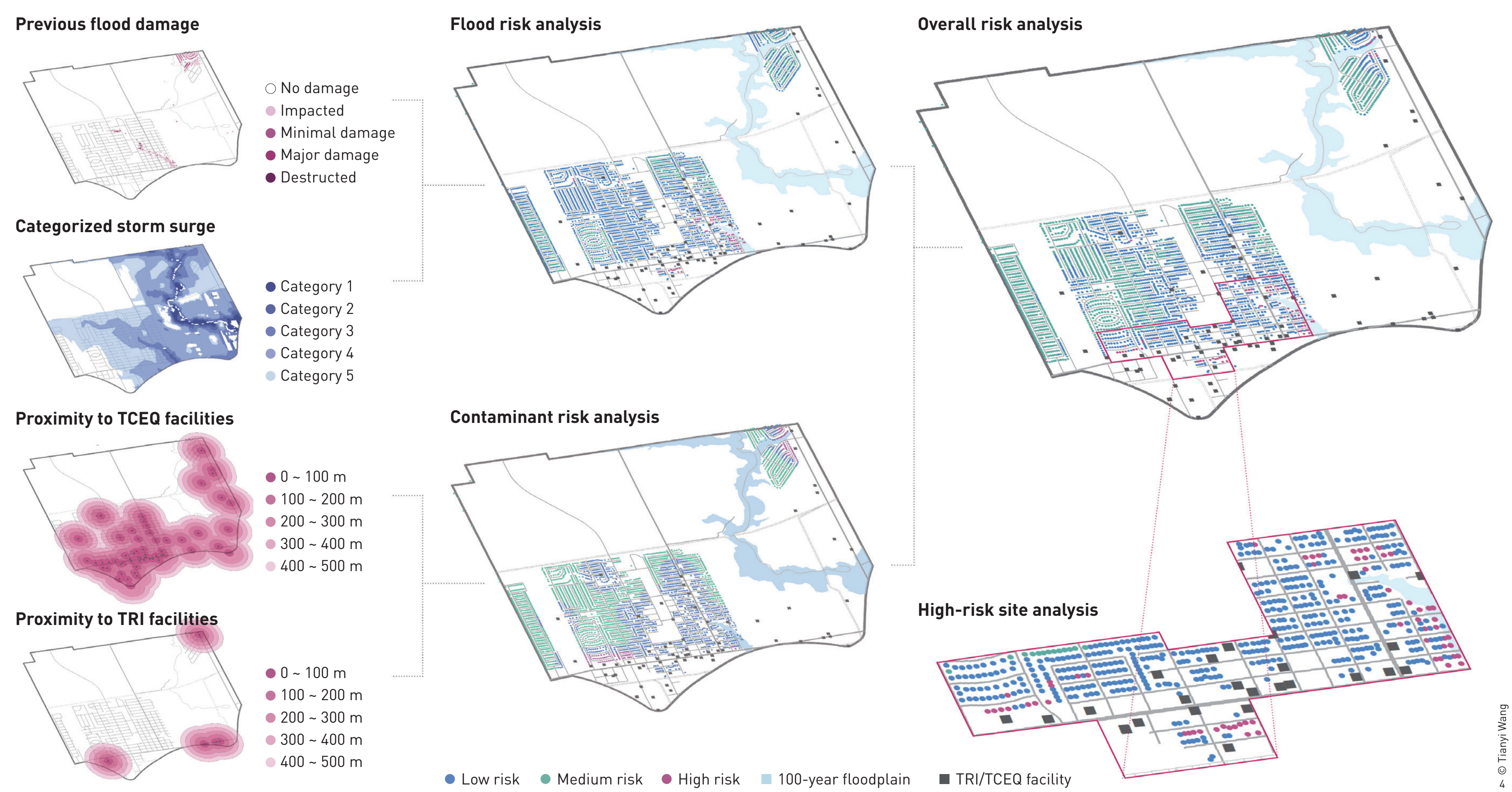
used to decrease flood vulnerability and exposure to industrial contaminants in Galena Park. The toolkit was created based on the Low Impact Development Approaches Handbook prepared by Clean Water Services[27] by examining the space needed for each GI type and the depth of its root systems. It can, therefore, be applied according to specific on-ground spatial size (e.g., right of way widths) and underground depth of obstruction (e.g., gas and water pipe depths). An important concern of incorporating GI within the limited Right-of-Way (ROW) width is retaining sufficient driving lanes and pedestrian trails, as well as maintaining sufficient roadside parking availability. In Galena Park, the ROW width varies from street to street, so there are different concerns about the amount of space available for different GI practices. For ground spaces that are extremely constrained in size, such as less than 5 ft in width, GI facilities that can be integrated into existing development area with minimal extra surface space, such as vegetated walls, permeable trails, sand filters, and tree box filters, could be implemented.

Underground space should be carefully considered when implementing GI. Buried pipes and lines can be found at various depths, from cable lines at depths of 1 ft or less to gas lines at depths of 5 ft or deeper. When an underground pipe's depth is less than 3 ft, green parking, filter strips, and permeable paving can be applied without interrupting them. With the toolkit, we identified ROW widths and depths of underground utilities, and categorized them into ranges to install additional GI improvements and to propose a systematic GI implementation strategy (Fig. 3). The wider the ROW and the deeper the existing pipe is, the broader and more flexible the GI can be installed, because GI practices depend on soil and plants to mimic natural processes such as infiltration, evaporation, and transpiration to manage rainwater. As a result, the GI toolkit can be readily adapted to address flooding issues in any area, provided that a thorough assessment of soil conditions is conducted, and vegetation types are carefully selected to suit the local climate. Therefore, the flexible toolkit can guide future plan refinement based on the unique site conditions.

The GIS suitability model can be used to determine the overall risk level of buildings, which is a modeling approach to assessing the suitability or appropriateness of different locations for a specific purpose by assigning weights or scores to various criteria or factors relevant to the decision-making process[28]. The overall risk is measured by two essential factors, i.e., flood risk and contaminant risk. In this case, flood risk was determined using previous flood damage and categorized storm surge data[29], while contaminant

3. Challenged by limited developable space and complex underground pipe systems, the adaptive GI toolkit can be applied based on both on-ground spaces (such as ROW widths) and underground spaces (such as gas and water pipe depths), as spatial conditions allow.





4. The estimated overall risk level of an example building utilizing the GIS suitability model.

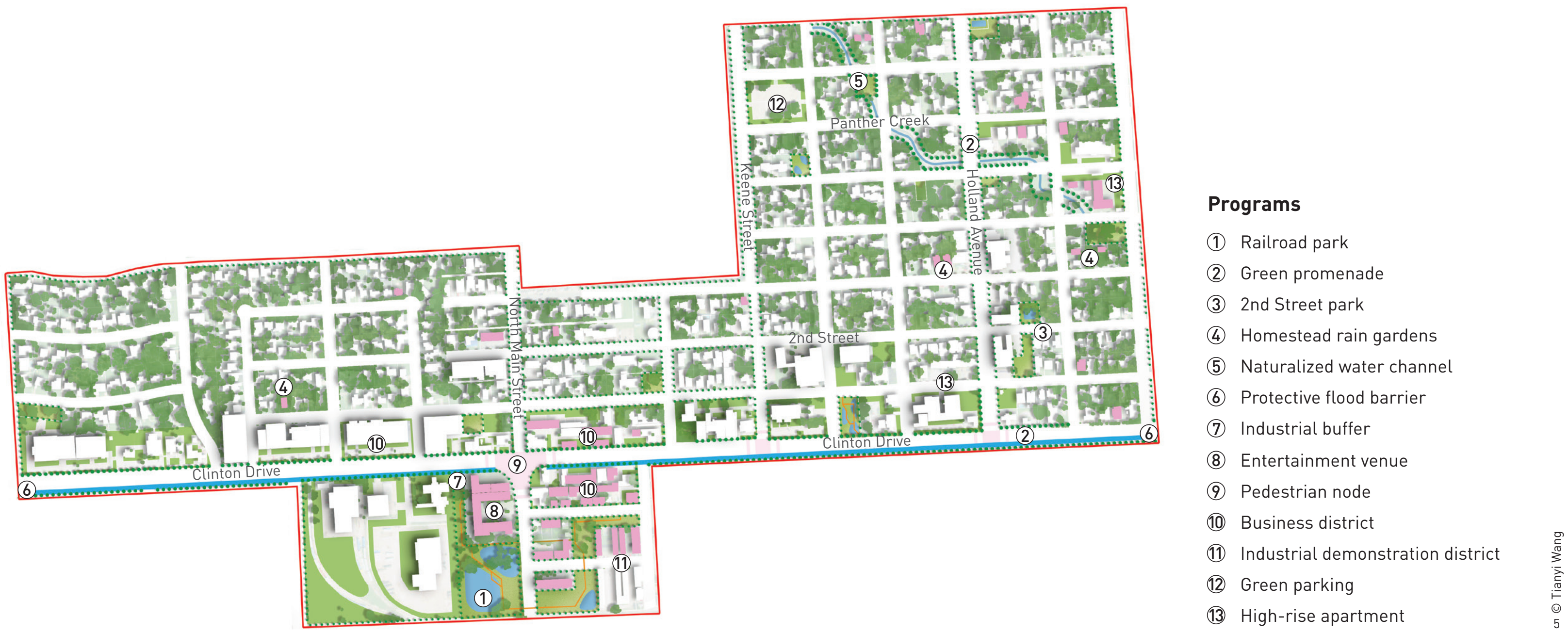
risk was determined using distance from TCEQ and TRI facilities. To facilitate a comprehensive analysis, we transformed these factors into maps (Fig. 4) and further categorized them into five distinct classes based on their index values. Each category represents a specific flood risk level, ranging from "1" for the lowest risk (indicating the most suitable to live) to "5" for the highest risk (indicating the least suitable to live). Consequently, the flood damage ranged from little damage (1) to destructed (5), the categorized storm surge ranged from category 1 (1) to category 5 (5), and the proximity to TCEQ and TRI facilities ranged from 0 ~ 100 m (5) to 400 ~ 500 m (1).

In order to ensure equal consideration for both flood and contaminant risks, we uniformly applied weights for the suitability model. This approach, which assigns equal importance to both factors, is commonly employed in spatial overlays within the existing literature[30]. By avoiding excessive weighting of specific variables, this method helps minimize potential biases in the outputs[31]. The estimated results indicate that a small number of residential buildings at the south of the city with a higher overall flood and pollutant risk (less than 5% of the total amount of buildings) should be relocated and replaced with green spaces or other non-residential buildings with elevated first floors.

3 Design Approaches and Details

The master plan of the target site in Galena Park is shown in Figure 5. Three phases of the master plan are described as below.

1) Phase 1 Developing Incubators (0 ~ 5 years). Phase 1 is to focus on 9.5 acres of major business development at the intersection between two major arterials—Clinton Drive and North Main Street. This business zone will serve as a hub of the community. This phase will incorporate 0.2 acre of green space into



5. The target site in Galena Park is at the highest risk level of both flooding and industrial contamination. In order to efficiently reduce the impact of floods, several GI practices in the toolkit are applied throughout the site.

the area to provide ecological benefits and promote the economic development of the site. To efficiently reduce the impact of floods, a protective flood barrier will be built along Clinton Drive which spans across the community from west to east (Fig. 5). Additionally, several GI practices from the toolkit, such as infiltration basins, bioswales, and planter boxes, are planned to be implemented in strategic locations near the business zone. These GI practices will be applied in North Main Street and sections of Clinton Drive to further mitigate inland flooding.

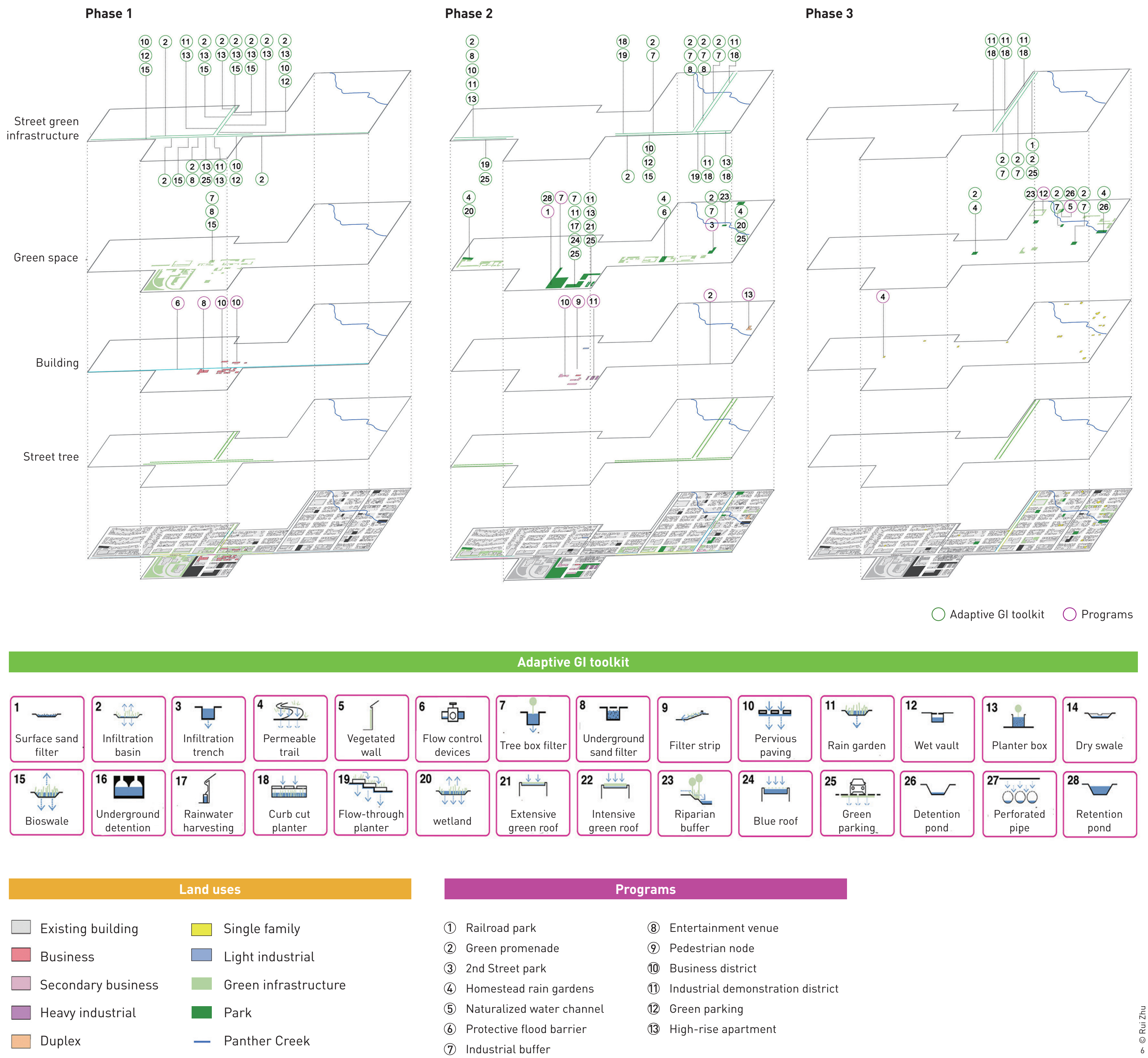
2) Phase 2 Feeder Development (5 ~ 10 years). Phase 2 will focus on the expansion of commercial and light industrial land uses in secondary areas covering approximately 3.5 acres. This area is to be located south of the main business zone, aiming to further stimulate economic development. Approximately 2.8 acres of parks featuring GI, such as retention pond, rain garden, and green parking, are implemented along Clinton Drive, spanning from the west to the east, and Holland Avenue in the eastern region of the community. Their purpose is to reduce the risk of flooding and pollutants and to provide spaces for residents' social activities.

And 3) Phase 3 Peripheral Facilities Development (10 ~ 15 years). Phase 3 will focus on improving 1.9 acres of single-family development across the site. In the east-north region along Panther Creek, 1.6 acres of GI are to be constructed to prevent flooding of the creek. Additionally, the GI toolkit will be implemented along Keene Street, an eastern secondary street, to connect other GI installations and establish an interconnected stormwater management system.

4 Assessment and Evaluation

Figure 6 and Table 1 show the detailed implementation of GI practices from the toolkit in the site. Overall, after implementation, the master plan will add 41% of commercial space and 450% of green space while reduce 36% of industrial area and 25% of residential area (Table 1). Several types of GI from toolkit will be applied in newly created green spaces and existing streets to form an interconnected GI system to improve drainage and decrease contaminants.

To assess the performance of Galena Park's master plan, the L-THIA/LID model was utilized to estimate the annual average stormwater runoff and pollutant loads of land-use configurations for each phase based on the city's daily precipitation data, soil type, land-use data, and LID practice percentages. Results show that the average annual stormwater runoff of Phase 1 may decrease by 4.6%, with an accumulated decrease of 13.0% by Phase 2 and a total decrease of 14.0% by Phase 3. Phase 1 will reduce the total amount



6. Detailed implementation plan for three phases of the site.

Table 1: Land use area for each phase

Land use	Current (acre)	Phase 1	Phase 2	Phase 3
Commercial	30.7	40.2 (31%)	43.2 (41%)	43.5 (42%)
Industrial	11.4	10.2 (–11%)	9.6 (–16%)	7.2 (–37%)
Multi-family	44.5	38.0 (–15%)	36.6 (–18%)	35.2 (–21%)
Single-family	87.2	85.5 (–2%)	81.7 (–6%)	83.6 (–4%)
Green space	1.0	1.2 (20%)	3.9 (290%)	5.5 (450%)
Others	34.5	34.2 (–1%)	34.3 (–1%)	34.3 (–1%)

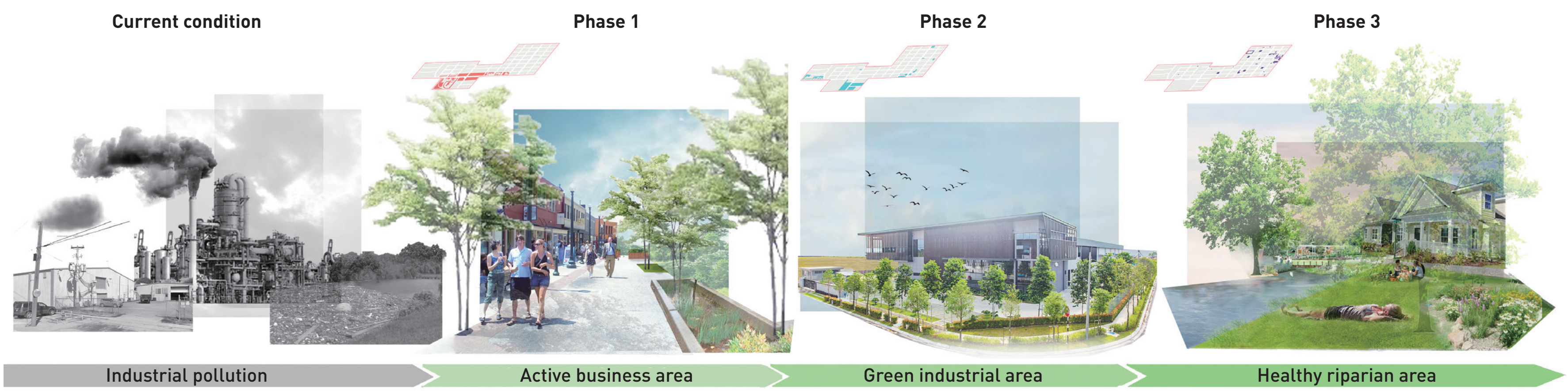
NOTE
The percentages in parentheses represent the percentage change between each phase and the current land use.

of chemical NPS pollutants by 0.6%, and 11.4% and 12.8% by Phase 2 and Phase 3, respectively. In terms of bacterial NPS pollutants including fecal coliform and fecal streptococcus, there will be 6.3% and 6.5% reduction after Phase 1, 11.6% and 12.9% reduction after Phase 2, and 12.0% and 13.7%reduction after Phase 3, respectively (Fig. 7).

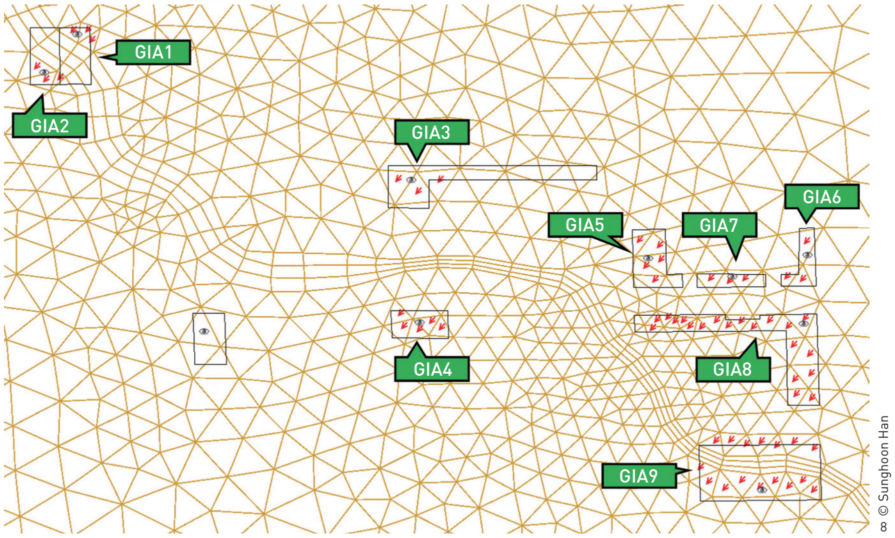
In order to determine the impact of the master plan on flooding from rainfall and/or storm surge, as noted, the Delft3D-FM model[32] was applied. This computational model solves the dynamical equations for shallow-water fluid flowing on a geographic grid, upon which environmental variables such as water depth, terrain elevation, wind velocity, tidal elevation, surge height, and waterway discharge rate can be input. The output consists of wave heights, water levels and velocities, (if activated) sediment transport, and changes to topography. The model is capable of running on a variety of platforms, from desktop PCs to supercomputing facilities. The grid used by the model is not limited to rectangular-shaped cells and can thus be manipulated to fit into complicated shorelines and waterway geometries. For this application, the overall grid extends from the Florida and Yucatan Straits in the south-eastern Gulf of Mexico, to the westward extent of the Houston Ship Channel. Terrain data for the coastal area came from the Coastal Relief Model[33] which has a spatial resolution of 3 arc-seconds (approximately 100 m at the latitude of the area).

To represent hurricane surge, we used wind field information (Hurricane Ike, which attacked Galveston Bay and Houston in September 2008) from the HURDAT2 database to drive the model. Since the actual landfall point was along the western edge of Galveston Bay, the strongest winds associated with the hurricane were located east of the bay. In order to determine the impact of the master plan on flooding under severe conditions (maximizing the surge and thus providing a strenuous test of the master plan), the landfall point of the simulated hurricane was manually shifted within the model a distance of 50 km to the southwest from its actual location to place the strongest hurricane winds over Galveston Bay. In addition to hurricane surge, both waves and tides present within the Gulf of Mexico area were also included. As a proxy for representing rainfall, discharge information for Panther Creek recorded over the duration of the storm was input

7. The estimation of the annual stormwater average runoff and pollutant loads for each phase calculated with the L-THIA/LID model.



© Rui Zhu
7



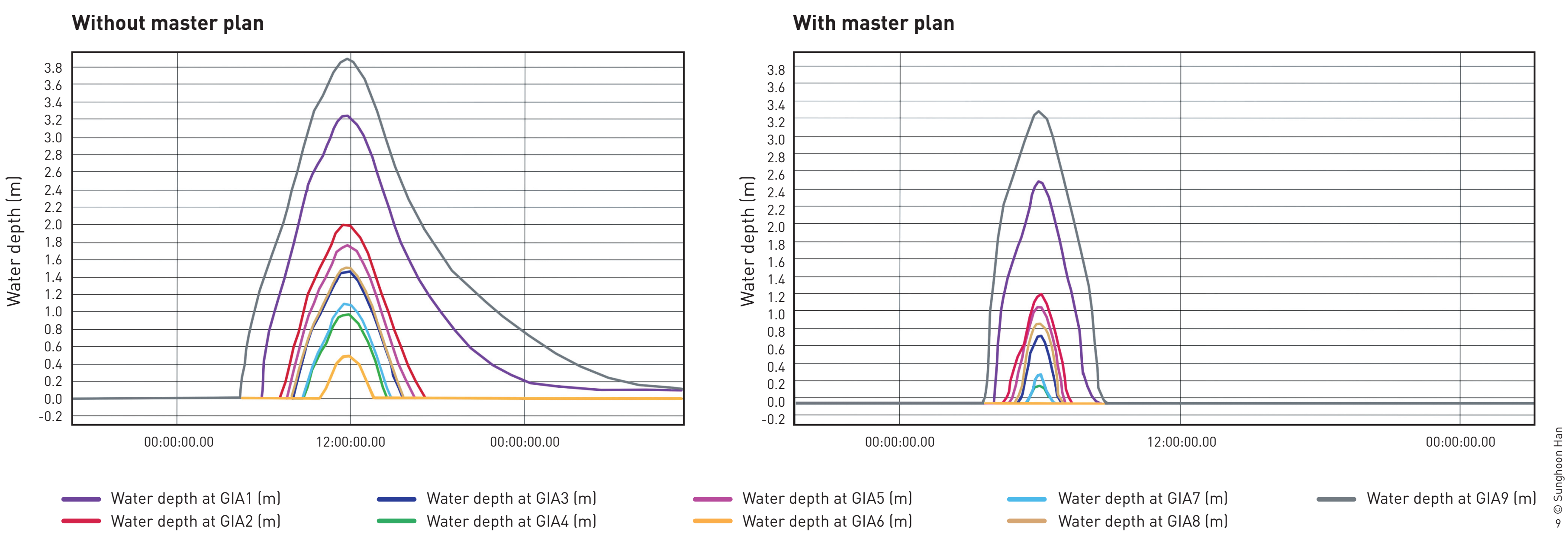
8. Map showing the sink points in the model terrain and the observation points.
9. A time series of inundation (recorded at the observation points) for the modified Hurricane Ike case with/without the incorporation of the master plan.

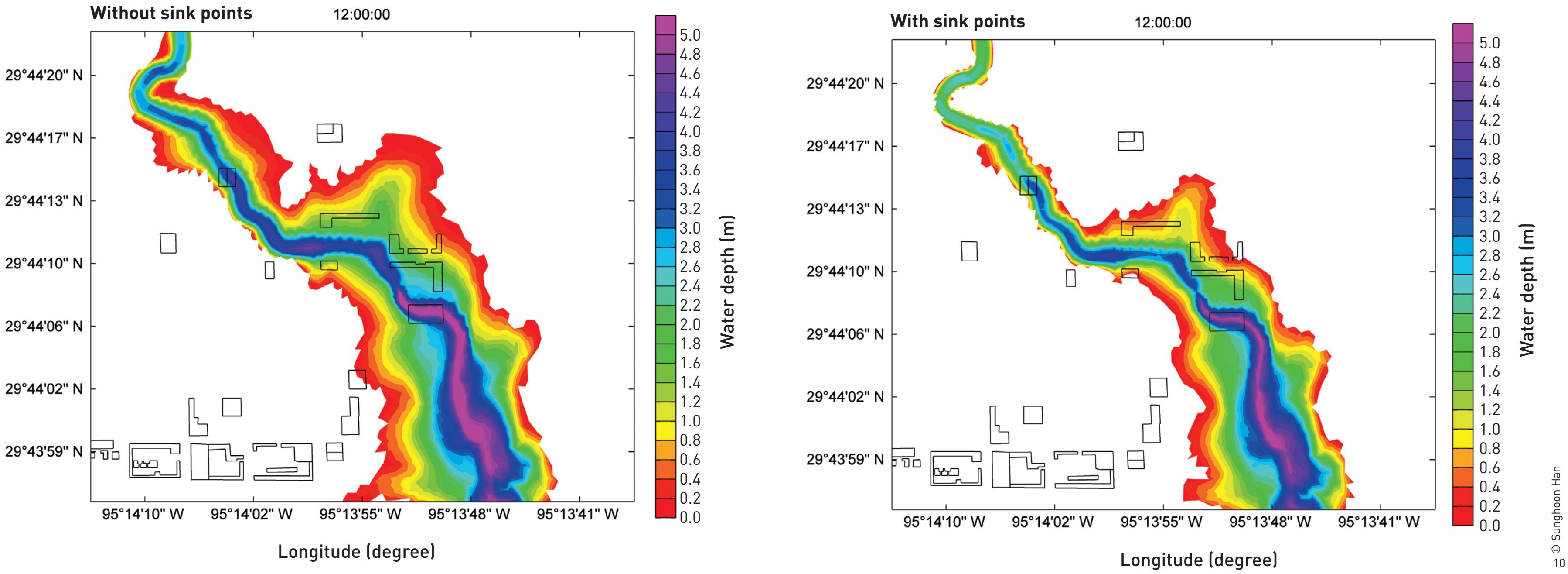
into the model. This was done under the reasonable presumption that the surface runoff in the area contained the entirety of the hurricane-induced rainfall, and all of the runoff eventually discharged into Panther Creek. As a result, the inclusion of this discharge information into the model is considered a sufficient accommodation for rainfall input.

The GI on the Panther Creek riverbank area at Phase 3 was incorporated into the Delft3D-FM model, with the green space drainage represented as "sink points" in the model terrain. These sink points are evenly distributed over each green space area (demarcated by arrows in Fig. 8). Each sink point is assigned an outlet flow rate that will dictate the drainage. Figure 8 also shows "observation points" (demarcated by the eyes), which are locations where the model records inundation depth. Figure 9 shows a time series of inundation (recorded at the observation points) for this modified Hurricane Ike case, both with and without the incorporation of the master plan. The results show that not only is the overall maximum flood depth less with the master plan in place, the amount of time the flood lasts is much shorter with the master plan. A comparison of flooding scenarios with and without the master plan revealed notable reduction of both the magnitude and the spatial extent of the flooding (Fig. 10). The areal extent and peak flood volume were both reduced by approximately 30% through the suggested interventions of the master plan (Table 2). Furthermore, the duration of the flood, measured from the onset of flooding to the complete recession of floodwaters, experienced a notable reduction. This reduction was particularly evident in area GIA1 (Fig. 11), which had the largest overall inundation. The flood duration in this area decreased from approximately 38 hours to around 10 hours due to the implementation of the master plan.

5 Discussion and Reflection

When dealing with fully developed areas which have limited ROW and complex underground utilities, planners and designers might be hesitant or not know how to best apply or implement GI,

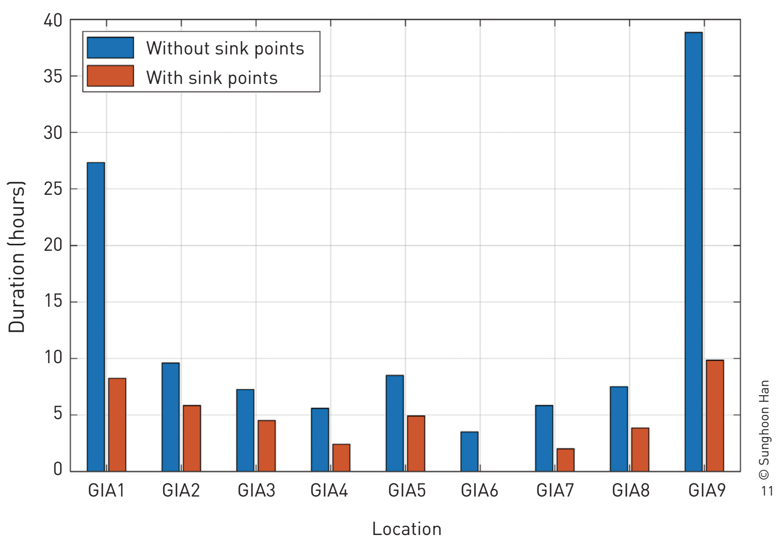




10. The flooding extent and depth at the storm peak with/without the master plan.

Table 2: Overall inundation volume and areal extent of inundation at the storm peak as calculated with the Delft3D-FM model

Scenario	Inundation volume at maximum surge (m^3)	Areal extent at maximum surge (m^2)
Without master plan	449,493	270,029
With master plan	315, 312	191,018



11. Flooding duration by hours recorded at observation points.

believing that managing rainwater through GI would require large areas of open land and inhibit compact development. This study shows how GIs could be implemented in retrofit projects and can have sound performance in reducing annual stormwater runoff and NPS pollutants under hurricane scenarios. The immediate health impact, such as decreased drowning, animal bites, injuries, and poisoning, and the long-term health impacts, such as poor mental health, chronic diseases (e.g., stroke, asthma, high blood pressure, coronary heart disease), and disability, can be largely reduced. In addition, indirectly, the city will also save on health care spending and reduce the financial loss by the damage and destruction to property, public areas, and the environment. The combination of L-THIA/LID and Delft3D-FM models provides solid evidence that it is feasible to implement GIs in fully-developed retrofit projects and these GIs can improve water quality and reduce rainfall-induced inland and hurricane-induced flooding, which is not achievable with grey infrastructure. GI is a cost-effective approach in the long-run and can be seen as a best preventive means of dealing with future increases in flood events. This study could lobby governments to prioritize GI in the urban renewal process. In addition, the GI toolkit can be employed for flood mitigation in similar cities.

This study sets the first example of the use of different types of GI facilities that can be integrated into existing developed areas with minimal extra surface space. More importantly, this study pioneers the use of Delft3D-FM in combination with the L-THIA/LID model to project the probable impact of the master plan on flood reduction, setting a precedent for more precise landscape performance assessments in flood mitigation design. Exploring more sophisticated modeling techniques like Delft3D-FM to evaluate design performance can largely improve the credibility of designs, thus helping overcome barriers in GI implementation.

However, the study does have some limitations. The L-THIA/LID model assumes that future climate conditions and land use changes will follow historical patterns. This assumption may impact the accuracy of the model's predictions, as climate change and land use dynamics are non-stationary in reality. Additionally, limitations of the Delft3D-FM model include the reliance on historical storm records, which may be insufficient for a comprehensive analysis. There are several such databases extant[34], however, the selection of appropriate databases would require extensive testing, which exceeds the scope of this study. Thus, at this stage, we believe that a limited set of simulations is sufficient to demonstrate the efficacy of the master plan with Delft3D-FM in ameliorating flooding.

Given the dependence of the Delft3D-FM model on terrain settings, it may be questioned whether the model provides significant value for flood analysis due to accuracy problems of terrain elevation. However, relevant hurricane surge study shows that the Coastal Relief Model used herein is of sufficient accuracy for inundation modeling[35]. In addition, the terrain of the region is continuously updated via the Continuously Updated Digital Elevation Model[36]. Further, both flood levels and duration have been identified as relevant descriptors of flood severity[37], and the Delft3D-FM system is able to represent both conditions caused by either inland flooding and/or hurricane driven surge. Finally, due to the unstructured mesh in Delft3D-FM, it is possible to represent various features of the master plan with extremely high mesh resolution in localized areas, thereby saving computational time overall while including these features with high fidelity.

PROJECT INFORMATION

LOCATION: Galena Park, TX, USA
AREA (SIZE): 209.3 acres
CLIENT: City of Galena Park, TX, USA
LANDSCAPE DESIGN: Texas A&M University, Center for Housing and Urban Development
CHIEF DESIGNER: Tianyi Wang
PROJECT TEAM: Tianyi Wang, Rui Zhu, Galen Newman
COLLABORATORS: Sunghoon Han, James Kaihatu
DESIGN PERIOD: May 1, 2021 ~ December 31, 2022
CONSTRUCTION PERIOD: From May 2023 to present
AWARDS: “Adaptive Stormbox—Flexible Green Infrastructure Assemblage Units for Galena Park, TX,” 2023 Merit Award, Planning and Analysis Category, American Society of Landscape Architects, Texas Chapter

RESEARCH FUND

National Institute of Environmental Health Sciences Superfund Grant (No. P42ES027704-01)

REFERENCES

[1] Newman, G. D., Qiao, Z., & Zhu, R. (2022). Sea level rise as a design and planning issue. In: G. D. Newman & Z. Qiao (Eds.), *Landscape Architecture for Sea Level Rise*. Routledge.

[2] Kirsch, K. R., Newman, G. D., Zhu, R., McDonald, T. J., Xu, X., & Horney, J. A. (2022). Applying and integrating urban contamination factors into community garden siting. *Journal of Geovisualization and Spatial Analysis*, (6), 33.

[3] Han, I., Whitworth, K. W., Christensen, B., Afshar, M., Han, H. A., Rammah, A., Oluwadairo, T., & Symanski, E. (2022). Heavy metal pollution of soils and risk assessment in Houston, Texas following Hurricane Harvey. *Environmental Pollution*, (296), 118717.

[4] Carter, J. M., & Kalman, C. (2019). *Future floods & superfund sites: Toxic contamination risks in coastal communities*. In: American Geophysical Union Fall Meeting 2019, San Francisco, CA, United States.

[5] Newman, G., Li, D., & Park, Y. (2022). The relationships between neighbourhood vacancy, probable PTSD, and health-related quality of life in flood-disaster-impacted communities. *Urban Studies*, 59(15), 3077–3097.

[6] Du, W., FitzGerald, G. J., Clark, M., & Hou, X. -Y. (2010). Health impacts of floods. *Prehospital and Disaster Medicine*, 25(3), 265–272.

[7] Environmental Protection Agency, United States. (2015). *Green infrastructure design and implementation*.

[8] Jayasooriya, V. M., & Ng, A. W. M. (2014). Tools for modeling of stormwater management and economics of green infrastructure practices: A review. *Water, Air, and Soil Pollution*, 225(8), 1–20.

[9] Ma, Y. (2004). L-THIA: A useful hydrologic impact assessment model. *Nature and Science*, 2(1), 68–73.

[10] Tang, Z., Engel, B. A., Pijanowski, B. C., & Lim, K. J. (2005). Forecasting land use change and its environmental impact at a watershed scale. *Journal of Environmental Management*, (76), 35–45.

[11] Liu, Y., Bralts, V. F., & Engel, B. A. (2015). Evaluating the effectiveness of management practices on hydrology and water quality at watershed scale with a rainfall-runoff model. *Science of the Total Environment*, (511), 298–308.

[12] Lim, K. J., Engel, B. A., Kim, Y., Bhaduri, B., & Harbor, J. (2001). Development of the Long Term Hydrologic Impact Assessment (LTHIA) WWW systems. In: D. E. Stott, R. H. Mohtar & G. C. Steinhardt (Eds.), *Sustaining the Global Farm* (pp. 1018–1023). Selected papers from the 10th International Soil Conservation Organization Meeting.

[13] Newman, G., Kim, Y., Joshi, K., & Liu, J. (2020). Integrating prediction and performance models into scenario-based resilient community design. *Journal of Digital Landscape Architecture*, (5), 510–520.

[14] Sangchini, E. K., Ownegh, M., Sadoddin, A., & Mobarhan, E. Y. (2020). Predicting the impacts of land cover management scenarios on the run-off volume and river pollutants using the L-THIA model for the Hablehrud Basin. *Watershed Management Research Journal*, 33(3), 36–52.

[15] Muñoz, D. F., Yin, D., Bakhtyar, R., Moftakhari, H., Xue, Z., Mandli, K., & Ferreira, C. (2021). Inter-model comparison of Delft3D-FM and 2D HEC-RAS for total water level prediction in coastal to inland transition zones. *Journal of the American Water Resources Association*, 58(1), 34–49.

[16] Harris County Flood Control District. (2002). *Tropical Storm Allison "Off the Charts" Report*.

[17] Harris County Flood Control District. (2009). *Ike Storm Surge Inundation Map*.

[18] Federal Emergency Management Administration (FEMA). (2018). *FEMA - Harvey Flood Depths Grid, HydroShare*.

[19] Mezzacapo, M., Donohue, M. J., Smith, C., El-Kadi, A., Falinski, K., & Lerner, D. T. (2020). Hawai'i's cesspool problem: Review and recommendations for water resources and human health. *Journal of Contemporary Water Research & Education*, (170), 35–75.

[20] Zhu, R., & Newman, G. (2021). The projected impacts of smart decline on urban runoff contamination levels. *Computational Urban Science*, 1(1), 2.

[21] Bilotta, G. S., & Brazier, R. E. (2008). Understanding the influence of suspended solids on water quality and aquatic biota. *Water Research*, 42(12), 2849–2861.

[22] Gaffield, S. J., Goo, R. L., Richards, L. A., & Jackson, R. J. (2003). Public health effects of inadequately managed stormwater runoff. *American Journal of Public Health*, 93(9), 1527–1533.

[23] Prüss-Ustün, A., Vickers, C., Haefliger, P., & Bertollini, R. (2011). Knowns and unknowns on burden of disease due to chemicals: A systematic review. *Environmental Health*, 10(9), 1–15.

[24] Schoeters, G., Den Hond, E., Zuurbier, M., Naginiene, R., Van Den Hazel, P., Stilianakis, N., Ronchetti, R., & Koppe, J. G. (2006). Cadmium and children: Exposure and health effects. *Acta Paediatrica*, 95(s453), 50–54.

[25] Centers for Disease Control and Prevention. (2020). *500 Cities Project: 2016 to 2019 | PLACES: Local Data for Better Health*.

[26] National Oceanic and Atmospheric Administration. (n.d.). *Saffir-Simpson Hurricane Wind Scale*.

[27] Clean Water Services. (2009). *Low Impact Development Approaches*.

[28] Rowden, A. A., Anderson, O. F., Georgian, S. E., Bowden, D. A., Clark, M. R., Pallentin, A., & Miller, A. (2017). High-resolution habitat suitability models for the conservation and management of vulnerable marine ecosystems on the Louisville Seamount Chain, South Pacific Ocean. *Frontiers in Marine Science*, (4), 1–19.

[29] Zachry, B. C., Booth, W. J., Rhome, J. R., & Sharon, T. M. (2015). A national view of storm surge risk and inundation. *Weather, Climate, and Society*, 7(2), 109–117.

[30] Newman, G., & Kim, B. (2017). Urban shrapnel: Spatial distribution of non-productive space. *Landscape Research*, 42(7), 699–715.

[31] Prybutok, S., Newman, G., Atoba, K., Sansom, G., & Tao, Z. (2021). Combining Co$ting Nature and suitability modeling to identify high flood risk areas in need of nature-based services. *Land*, 10(8), 1–17.

[32] Deltares. (2018). *D-Flow Flexible Mesh: D-Flow FM in Delta Shell, User Manual*.

[33] National Geophysical Data Center. (2001). *Topography and Digital Terrain Data*.

[34] Nederhoff, K., Hoek, J., Leijnse, T., van Ormondt, M., Caires, S., & Giardino, A. (2021). Simulating synthetic tropical cyclone tracks for statistically reliable wind and pressure estimations. *Natural Hazards and Earth System Sciences*, 21(3), 861–878.

[35] Hope, M. E., Westerink, J. J., Kennedy, A. B., Kerr, P. C., Dietrich, J. C., Dawson, C., Bender, C. J., Smith, J. M., Jensen, R. E., Zijlema, M., Holthuijsen, L. H., Luettich Jr., R. A., Powell, M. D., Cardone, V. J., Cox, A. T., Pourtaheri, H., Roberts, H. J., Atkinson, J. H., Tanaka, S., Westerink, H. J., & Westerink, L. G. (2013). Hindcast and validation of Hurricane Ike (2008) waves, forerunner, and storm surge. J*ournal of Geophysical Research: Oceans*, 118(9), 4424–4460.

[36] Cooperative Institute for Research in Environmental Sciences (CIRES). (2014). *Continually Updated Digital Elevation Model (CUDEM) - 1/9 arc-second resolution bathymetric-topographic tiles [Atlantic and Gulf Coasts]*. NOAA National Centers for Environmental Information, Boulder, CO, United States.

[37] Kvočka, D., Falconer, R. A., & Bray, M. (2016). Flood hazard assessment for extreme flood events. *Natural Hazards*, (84), 1569–1599.

https://doi.org/10.15302/J-LAF-1-040031

中图分类号 | TU985, X52　　文献标识码 | B

利用适应性工具包评估绿色基础设施在减少暴雨径流和污染负荷方面的效用——以美国得克萨斯州加利纳帕克市为例

朱芮[1,*]，盖伦·纽曼[1]，韩成勋[2]，詹姆斯·凯哈图[2]，王天怡[1]

*通讯作者邮箱：zr1991@tamu.edu

1 美国得克萨斯农工大学景观设计与城市规划系，大学城 77843
2 美国得克萨斯农工大学扎克里土木与环境工程系，大学城 77843

图文摘要

文章亮点

- 适应性绿色基础设施工具包有助于降低城市地区的洪水脆弱性和接触工业污染物的可能性
- 整合L-THIA模型和Delft3D-FM模型，动态评估暴雨径流和污染物的降低程度
- 适应性绿色基础设施工具包可以根据地面空间面积大小和地下障碍物的深度进行定制
- 适应性绿色基础设施工具包有助于通过总体规划来减少暴雨径流和非点源污染物的影响

关键词

暴雨径流；
污染负荷；
公共健康；
绿色基础设施工具包；
Delft3D-FM模型；
L-THIA模型

摘要

在空间受限、土地开发过度及拥有错综复杂地下市政设施网络的社区中，建设绿色基础设施来减少洪水及其相关污染困难重重。为应对这一挑战，作者开发了一种适应性绿色基础设施工具包，其可根据地面可用空间的面积大小和地下障碍物的深度进行个性化定制。本文以美国得克萨斯州加利纳帕克市为例——该市长期受到洪水及地面、地下空间限制的困扰——首先应用该工具包为城市制定了总体规划，而后利用Delft3D-FM模型和长期水文影响评价（L-THIA）模型评估了该规划的效果。评估结果显示，不同阶段的暴雨径流和非点源污染物均会减少，该工具包能够有效管理水资源和控制污染，可为面临类似挑战的社区提供参考。

收稿时间

2022-08-16

编辑 王颖，田乐