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Is Green Infrastructure Viable for Mitigating Pluvial Floods? A Retrospective Study of a Community Renovation Applying LID Principal and Practice in Zhenjiang City of China

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Abstract: Is GI (Green Infrastructure) viable to mitigate urban pluvial flood caused by extreme storm events? Limited research and planning have been undertaken in recent years, but little practice has been found in the real world. This retrospective study provides an example of mitigating pluvial flood by LID (Low Impact Development) principal and practices and transforming an old, ultra-dense low-income community into a climate change resilient community. The key findings include keeping flood control in mind when designing GI in the beginning; mimicking the sites' hydrologic characteristics as much as possible; outreaching to residences for maintenance issues from the beginning and monitoring the performance of GI facilities continuously. Technically, bioretention growing media with higher infiltration rate is specified that must be great than 150 mm/h in short term and 80 mm/h for long term; this paper chose low maintenance permeable pavement products avoiding clogging; and increasing parking space without compromising the design goals.

Key words: GI, LID, sponge city, pluvial flood, climate change, resiliency.

1. Introduction

Pluvial flood is generally a flood caused by extreme rainfall that was dumped into an area creating ponding or overland flow and exceeding natural or engineered drainage capacity. Due to the combined effects of urbanization and climate change pluvial flood has become a major threat to many cities in China. From 1990-2021 China has experienced the fastest urbanization in the history. China's urban population increased from approximately 302 million to 902 million, or from 26.4% to 63.9% of China's total population [1, 2]. Associated with urbanization, landscapes in developed areas have dramatically changed. The impervious surface area across Chinese cities has been steadily increasing at an annual rate of 6.5% from 1992 to 2009 [3]. However, the drainage and sanitary infrastructures' construction and upgrade cannot keep up with the urban expansion. This is especially true in low-income communities. Most of them are lacking in appropriate sanitary conditions and located in combined sewer zones. These factors combined with climate change attribute to the recent increase of pluvial flood in China [4-6].

In response to the disasters caused by pluvial flood the Chinese government has adopted a series of policies and programs to expedite and strengthen the development of drainage systems across cities. In 2014 the government formally announced a national initiative program named Sponge City Initiative. The actions have been undertaken for implementing the policy of Sponge City Constructions, including publishing a preliminary technical guideline [7],

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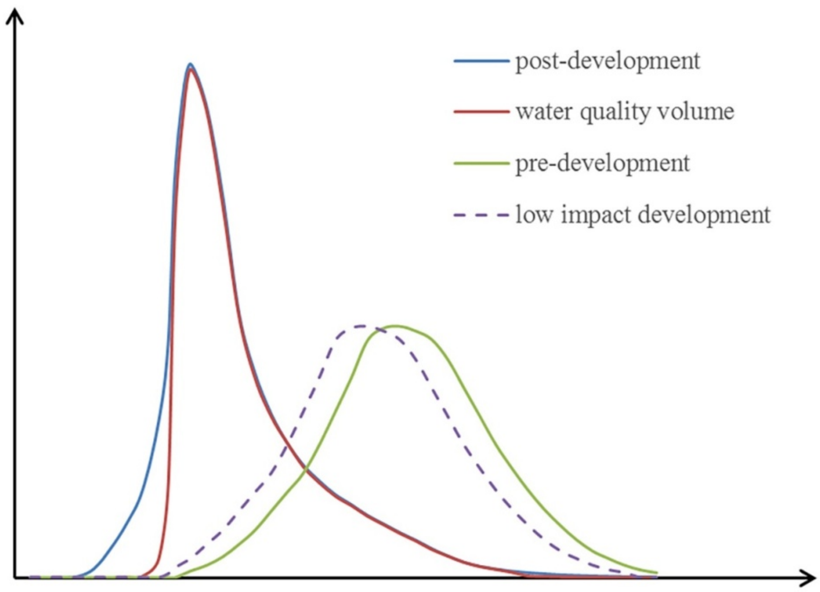


Fig. 1 Comparison of the hydrological response of WQv and LID to the extreme storm event.

setting targets, and establishing a regulatory framework. Three batches of cities were selected, 16 in 2015, 14 in 2016, and 20 in 2021.

The debate about whether GI (Green Infrastructure) is viable to mitigate pluvial flood has been an important issue from the beginning of the Sponge City Construction. The controversy is about the runoff volume control percentage set by the preliminary technical guideline, which is similar to the WQv (Water Quality Control Volume) in some states in the United States. Roughly speaking it is about to capture and treat approximately 90% of the average annual stormwater runoff volume. In most cases it is about 1″ rainfall depth and is solely targeting on pollution control [8, 9], while the LID (Low Impact Development) is quite different. Although LID projects may look like WQv projects, especially the bioretention cells, there are key differences that designers and contractors must consider. LID design begins at the site scale mimicking the hydrologic processes of a predevelopment landscape through infiltration, retention, detention, storage, peak shifting and delay techniques. Therefore, the design process, the goal and implementation are different from WQv. Fig. 1 shows the schematic hydrographs of WQv and LID that describe the hydrological response of a site to the extreme storm event.

In order to clarify the confusion about WQv and LID in design and implementation, this paper presents a retrospective study of using LID to retrofit a low-income community in Zhenjiang City of China into a pluvial flood resilient neighborhood. It shows an alternative approach to conventional way for flood mitigation and sewer separation. The paper is structured through introducing the background of the study and then describing the design and implementation processes. The results and discussion explore how LID can be implemented to manage pluvial flooding across a range of rainfall events in urban areas.

2. The Background of the Study

In 2015, Zhenjiang City, Jiangsu Province, was selected by the Chinese government as one of the first 16 cities as a sponge city pilot. The pilot area is 22 km^2 located within the heart of the old city. Hundreds of old communities are in a combined sewer zone. Some of them frequently suffer flooding and sewage

Fig. 2 The problems in the community before the renovation.

surcharges. According to the city's master plan these problems need to be solved by year 2020. More than 100 community renovation projects were prioritized through Sponge City Pilot Program. These projects need to meet the requirements set by Sponge City Initiative.

The community presented in this study named Riverside New Village is a low-income community that had many problems in common citywide. The problems included endured annual flooding, deterioration of aging infrastructure, lack of appropriate sanitary conditions and parking lot, no suitable space for leisure, recreation and social interaction (Fig. 2). Because of these poor living conditions, young people escaped from the community though it is within prime of Zhenjiang. Most residents living in the community were elderly and children.

For these reasons this community was chosen to apply LID principal and practice in both design and construction to demonstrate multiple benefits based on natural solutions. The benefits included flood control up to 30-year storm event, energy conservation, sanitary sewer separation and landscape upgrade. In the design process hydrologic models were used to guide the landscape architects and drainage engineers to achieve their goals.

The community is about 1.9 ha. Nine high density apartment complexes are located with the community. These complexes had some degree of leakage of water supply lines, illicit connections, and illegal garbage dumping problems. Only about 21% or 3,916 m^2 green space can be used for bioretention. To achieve the benefits mentioned above, the design team needs to involve multidisciplinary expertise. It was our intention to bridge the gaps between planners, landscape architects, civil engineers, government officers and citizens. All stakeholders expected that after the completion of the renovation the community would become an ideal place for social interactions of the residents, a happy place for retirees and children to play together, and a beautiful neighborhood for residents to relax reducing symptoms of depression and anxiety.

3. Design Process

3.1 Multi-objective Approach

In 2015 most people in China including urban planners, landscape architects and drainage designers did not hear about sponge city [10]. LID practices were often viewed as water management/treatment facilities but lost the landscape beauty [11-13]. Therefore, to integrate drainage features into landscape design is a challenge. On the other side, the residents had different expectations. Most residents demanded more parking spaces as the priority in addition to solving flooding and utility deterioration problems. Through investigation of the site and communications with the residents, this project envisions a new way to solve these problems using a multi-objective approach named "LID + N" elements, which include landscape improvement, energy conservation, utilization upgrades, installation of parking lot and preservation of urban farming.

3.2 Hydrologic Modeling

To guide the landscape architects and drainage engineers in LID designs, building an appropriate hydrologic model could be a powerful tool facilitating conversations with designers and residents. The design and modeling are an iterative process. The most challenging task is to prevent pluvial flood up to a 30-year storm event. In addition, the design must take into account other demands identified by all stakeholders making the community not only resilient to extreme weather conditions but also shinning in aesthetics. The iterative process started from building a hydrologic model simulating the runoff prior to the retrofit. The model built by Stormwater Management Model (SWMM) was run using a 30 year-24 h design storm event. The flooding locations, flood depth and durations were identified. Then a preliminary LID layout based on the site visiting and investigation was added into the model. The simulations were performed using the same design storm event. The results were analyzed to evaluate whether the LID layout satisfied the flood prevention goal. If the goal was not satisfied, then the layout must be modified, and the model would also be changed accordingly. The process would be repeated until the simulation result showed that the flood depth and duration in all locations were less than 15 cm and 30 min, respectively (Fig. 3), which is set as the urban flooding standard in China [14].

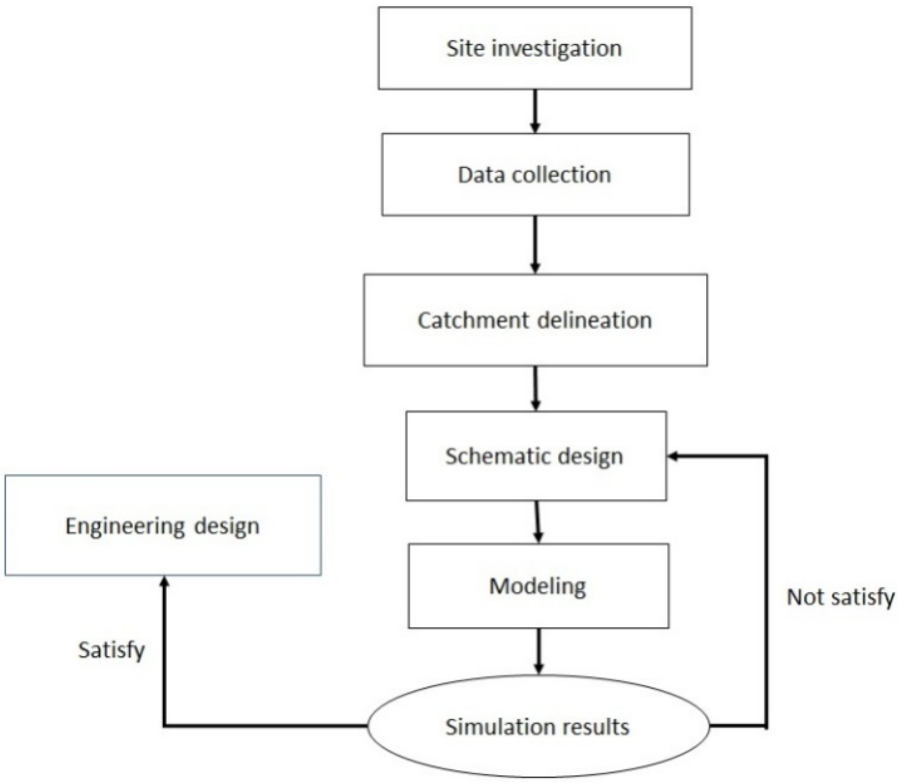
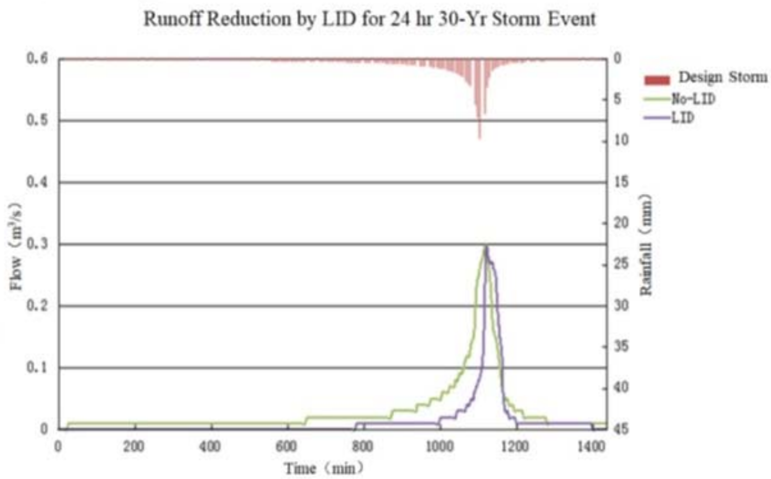


Fig. 3 The iterative process of modeling and design.



	Rainfall (mm)	Peak runoff (m^3/s)	Runoff volume (m^3)	Runoff coefficient
Before the renovation	220	0.3	3600	0.87
After the renovation	220	0.29	1860	0.46

Fig. 4 Identify of the flood locations using the hydrology model with and without LID.

Fig. 4 shows the flooding locations in the community with and without the LID. There were 24 flood locations without the LID; 14 of them exceeded the flood standard. By contrast, there were only 7 locations flooded with the LID, but none of them exceeded the flood standard. The final simulation result showed that the runoff volumes are reduced by 48%, the runoff coefficients are changed from 0.87 to 0.46 and flood locations are reduced from 24 to 7. This indicated that without increasing existing drainage pipes' capacity that was designed to convey one year storm event, the community is resilient to 30-year storm event.

3.3 Resilient Landscape Design

An important principal of LID is to mimic natural hydrology characteristics on site. These characteristics such as runoff volume, peak flow, flow duration, infiltration, evapotranspiration, and subsurface flow need to be integrated into a resilient landscape design. Fig. 5 shows an innovative approach to mimic sites' hydrologic characteristics as much as possible. It should be noted that this design reconnected subsurface flow that was cut off by impervious surface through the gravel layers. The gravel layers of bioretention and permeable pavement are interconnected and extend along the sidewalk as far as they can to maximize the subsurface flow path.

Other factors such as increasing parking lots and creation of social and recreational spaces were also needed to be considered in the design process. Since the density of the community is high and green space is low, it is a challenge for the designers to utilize the limited space to layout LID facilities. For examples, sidewalk was designed for dual functionalities that could be used for parking and for residents passing through safely. To share social and recreational space with bioretention, the play decks were laid on the top of planters in a way that runoff could be captured and treated underneath of the decks (Fig. 6).

Since this community has about 40 years of history, many residents wish keeping their memories by keeping some special features and landmarks, for example vegetable gardens. In general, "Design Minus

Fig. 5 A schematic resilient landscape design that mimics site's natural hydrologic process.

Fig. 6 Sharing bioretention with social and recreational space.

Principle" is developed and applied to minimize the landscape intervention. Because the community has no property and assess management entity, it is critical to minimize the maintenance cost, and encourage the residents to maintain these facilities voluntarily.

4. Implementation Process

4.1 Jobsite Management

Unlike general urban gardening and municipal landscape construction, LID installation is indeed an accurate engineering process. It requires contractors to take care of many details such as elevations, gradings, materials, vegetations, and following the design instructions precisely. Common mistakes in LID include use of the wrong plants or soil mix; incorrect placement or elevation of curbs and overflow inlets; and improper grading that hinders the stormwater runoff from entering the facility [15].

To avoid these common mistakes a series of training and workshops were given to the contractors before they entered to the job sites. Although LID features may look like conventional development projects, there are key differences for contractors to understand as part of correct performance of LID facilities. The contractors were required to carefully review construction documents and specifications for design elements, construction methods, special phasing, and new materials related to LID features that may impact performance or cost. They needed to understand the unique needs for construction sequencing of LID features, that need protection from compaction, erosion, sedimentation, and construction runoff. On the other side, the project managers were required to overlook the quality of the installation periodically. They were required to answer all questions on the jobsites. For example, grading of LID features is non-traditional and assumptions and changes to grades shown on plans should not be made without consulting the designer. If a problem was found, a correction must be taken immediately.

4.2 Construction Material Management

Bioretention is probably the most popular SCM (Storm Control Measures). Use of correct bioretention growing media and plants is very important to achieve a successful performance. The conflicts on how to choose growing media between landscape architects and drainage engineers have been a critical issue since the beginning of the Sponge City Initiative. In general landscape architects want nutrient rich, moisture, low infiltrated media while drainage engineers want nutrient poor, dryer, and high infiltrated media. A typical growing media adopted from Washington State of the United States is mixed with 60% coarse sand and 40% compost [16, 17]. But recent studies showed that compost based growing media export nutrients and heavy metals [18-20]. In this project landscape architects and drainage engineers agreed to test an alternative media which contains 50%-60% of coarse sand, 20%-25% of coconut coir and 15%-30% of selected topsoil (d > 25 μm). The short-term infiltration rate of the media must be greater than 150 mm/h, and the long-term infiltration rate must be greater than 80 mm/h.

To consider the landscape architects and residents aesthetic perception, four test lots were built for different combination of sand, coconut coir and topsoil. Thirty (30) popular plants were selected for the test. After 6 months observation a plant list was developed for the composition of 60% sand, 20% coconut coir and 20% topsoil because the plants health was the best for the composition (by visual observation). Table 1 is the plant list developed for the bioretention growing media specified above.

Permeable pavement is another SCM used in this project. However, choosing appropriate type of permeable pavement is curtail for performance and maintenance. Based on site investigation and observation of the residents' life pattern, preventing clogging and minimizing maintenance were two most important issues. From literature review [21-23] PICP (Permeable Interlocking Concrete Pavement) came to the first choice because of its permeability, strength, aesthetics, and sustainability. Before installation a 10 m^2 field test was conducted. The test was to evaluate the structure capacity and hydraulic efficiency. It was found that by simplifying the base structure using graded gravel only, the performance of the PICP is almost equal to that of typical ICBP (Interlock Concrete Block Paver) in strength, and in the case of 90% surface clogging, the infiltration rate is about 600 mm/h.

4.3 Community Outreach

During the construction period many community meetings and discussions were held in response to residents' concerns, requests and the conflict issues between the contractors and residents such as removal of illegal constructs that occupied the public green space, disconnection of illicit connections, plant species of the bioretention and some safety concerns. The most significant conflict issue is about the utilization of green space between vehicle owners and no-vehicle owners. Vehicle owners wanted to convert green space for parking lot, while no-vehicle owners

Table 1 A plant list for bioretention growing media (60% sand, 20% coconut coir and 20% topsoil).

Botanical name	Photo	Common name	Zone	Water	Tolerance	Sun	Depth of growing media(cm)
***Iris tectorum* Maxim**		roof iris	4-9	Medium	Drought	full sun to part shade	30
***Hemerocallis aurantiaca* Baker**		orange daylily	3-9	Medium	Drought, Erosion, Clay Soil, Air Pollution	Full sun to part shade	30
Rosmarinus officinalis		rosemary	7-10	Dry to medium	Drought, Shallow-Rocky Soil	Full sun	30
***Weigela floridacv . Red* Prince**		weigela	4-8	Medium	Clay Soil	Full sun	60
***Hylotelephium erythrostictum* (Miq.) H. Ohba**		stonecrop	3-9	Dry to medium	Drought, Clay Soil, Dry Soil, Shallow-Rocky Soil, Air Pollution	Full sun	30
***Oxalis corymbosa* DC.**		Lilac Oxalis	7-10	dry or moist soil	Suitable for light (sandy), medium (loamy) and heavy (clay) soils and prefers well-drained soil. Suitable pH: mildly acid, neutral and basic (mildly alkaline) soils.	Full sun	30
Forsythia suspensa		weeping forsythia	5-8	Medium	Clay Soil, Black Walnut	Full sun to part shade	60
***Pyracantha fortuneana* (Maxim.) Li**		Graber's Pyracantha	6-8	Medium	all soil types,drought tolerant	Full sun to part shade	60
Photinia x fraseri		Red Tip Photinia	7-9	Medium	Drought	Full sun to part shade	60
***Rhododendron simsii* Planch.**		Formosa Azalea	8-10	Medium	Drought，acidic; clay; loam; sand;	Part shade/part sun	60
***Spiraea x bumalda cv*.Gold Flame**		Japanese spirea	4-8	Medium	Erosion, Clay Soil, Air Pollution	Full sun	60
***Chimonanthus praecox* (Linn.) Link)**		wintersweet	7-9	Medium		Full sun to part shade	80
***Punica granatum* L. *var.nana* Pers**		dwarf pomegranate	7-11	Medium	Drought, Dry Soil	Full sun to part shade	80
Liriope spicata var.Variegata		creeping liriope	4-10	Medium	Drought, Erosion, Air Pollution	Full sun to part shade	20
***Aucuba japonica* Variegata**		spotted laurel	7-9	Medium	Heavy Shade, Clay Soil, Air Pollution	Part shade to full shade	60
***Hydrangea macrophylla* (Thunb.) Ser.**		bigleaf hydrangea	6-9	Medium	Best grown in rich, medium moisture, well-drained soils	Part shade	60
Ajania pallasiana		ajania	5-9	Medium	Grow in average, medium moisture, well-drained soils. It tolerate poor soils as long as drainage is good. Wet soils in winter can be fatal.	full sun to part shade	30
***Rosa chinensis* Jacq.**		China rose	6-9	Moist soil	Suitable for: light (sandy), medium (loamy) and heavy (clay) soils, prefers well-drained soil and can grow in heavy clay soil. Suitable pH: mildly acid, neutral and basic (mildly alkaline) soils.	Semi-shade or full sun	60
***Berberis thunbergii* DC.**		Japanese barberry	4-8	Dry to medium	Drought, Erosion, Clay Soil, Dry Soil	Full sun	60
***Acer palmatum* Thunb.**		Japanese maple	5-8	Medium	Best grown in moist, organically rich, slightly acidic, well-drained soils	Full sun to part shade	80
Pittosporum tobira		Japanese pittosporum	9-10	Medium	Drought	Full sun to part shade	60
***Bambusa multiplex* (Lour.) RaeuschelexJ.A.et J.H.Schult**		Hedge Bamboo	8-11	Medium	Suitable for: light (sandy) and medium (loamy) soils and prefers well-drained soil. Suitable pH: mildly acid, neutral and basic (mildly alkaline) soils.	Sun / Shade	60
Loropetalum chinense var.rubrum		Chinese fringe-flower	7-10	Medium	Suitable for: rich, humusy, acidic, moist, somewhat gritty, well-drained soils	Full sun to part shade	60

wanted more green space for gardening. To address concerns of both sides, the designers, contractors, and dispute parties worked together to develop a plan that maximized parking space and minimized the reduction of green space by creating micro-scale green mosaics that looked beautiful.

5. Results and Discussion

The project was completed in September of 2015. To evaluate the performance of GI a flow monitor was installed at the outlet of the community. The first year's monitoring data showed that the hydrology response was significant resulting in more than 95% of rainfall detained onsite (Fig. 7). Water quality response was also notable. The sediment accumulation was 40.9%-56.8% less than the communities without GI during 7 to 15 days of dry weather period. Specifically, the TSS (Total Suspended Solids) retention was 78.6%, COD (Chemical Oxygen Demand) retention was 88.2%, NH_4^+-N retention was 65.0%, TN (Total Nitrogen) retention was 78.7%, and TP (Total Phosphorus) retention was 80.2% [24].

In 2016 and 2017 the city was hit twice by 137.9 mm and 138.8 mm 24-h storms consecutively, the community had no ponding water in the surface. The LID facilities played their best role. Fig. 8 showed the hydrograph of a 138.8 mm/24 h heavy storm on June 6, 2017. This was a dual peak storm. The first peak of rainfall occurred at about 9:25 am, the corresponding runoff peak occurred at about 2:40 pm, approximately shifted 5.25 h. The second peak of rainfall occurred at about 4:45 pm, the corresponding runoff peak occurred at about 5:55 pm, shifted about 1.08 h.

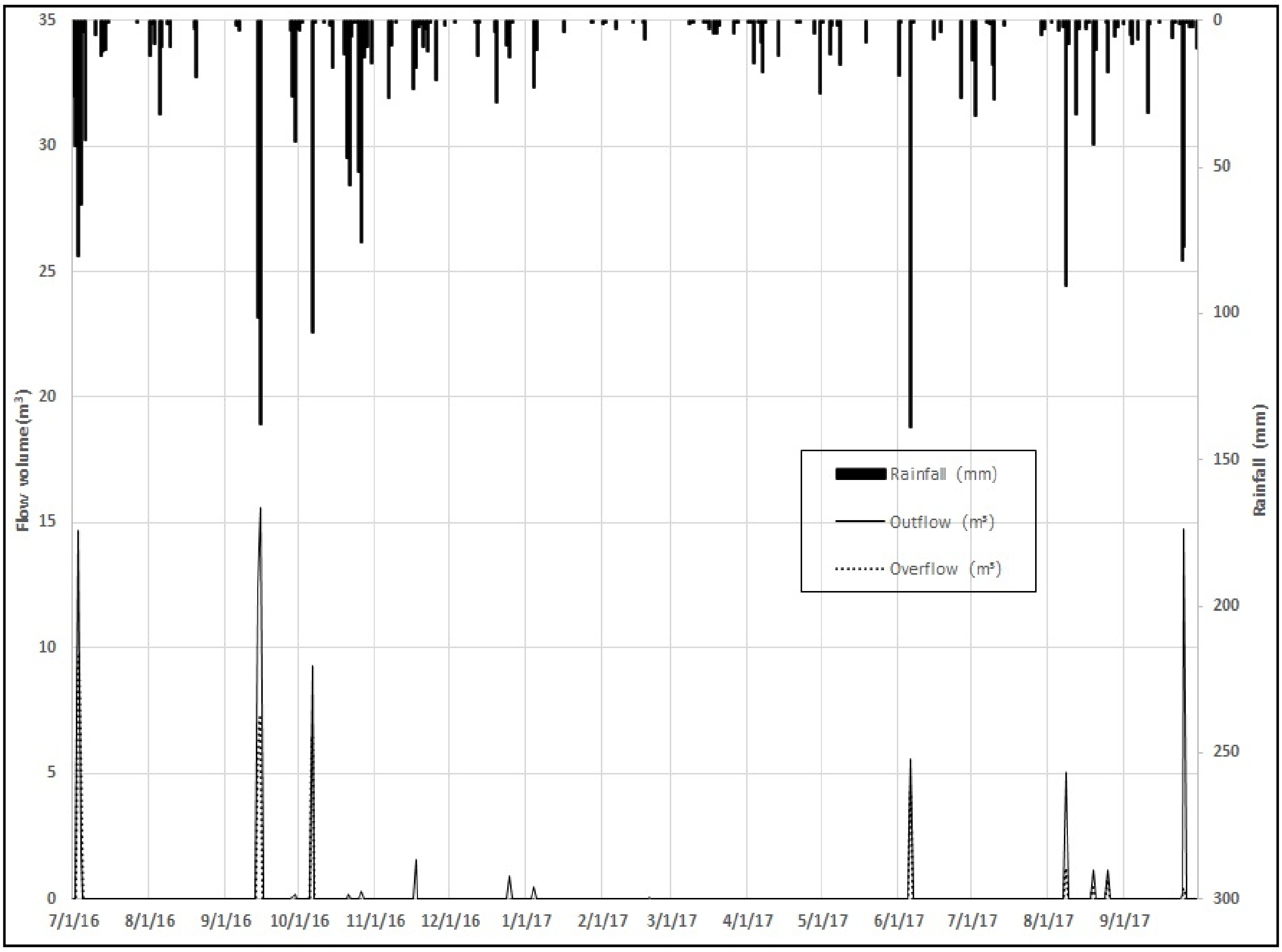


Fig. 7 One year (July 1, 2016, to Sept. 30, 2017) monitoring data of rainfall, outflow and overflow.

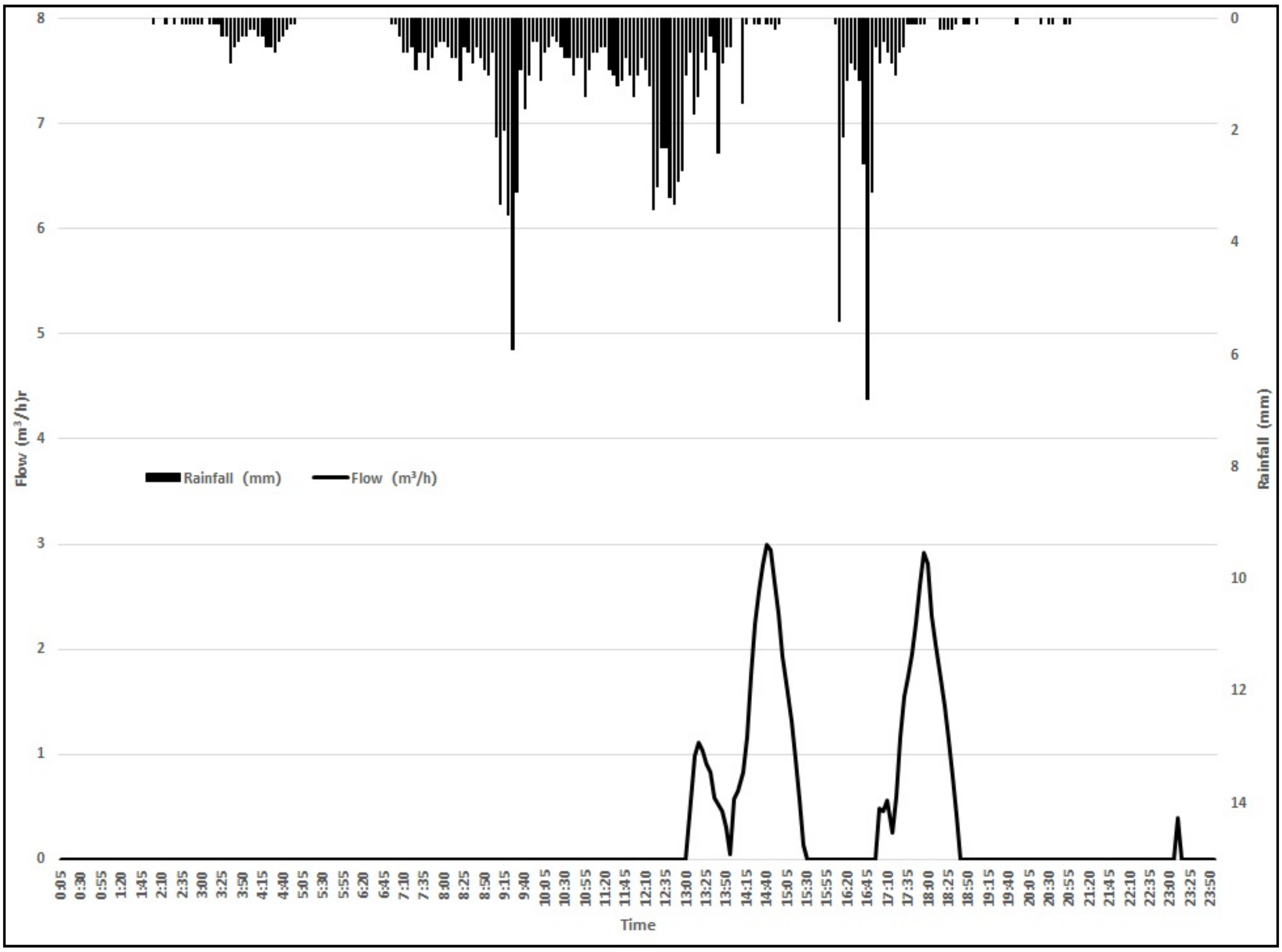


Fig. 8 The performance of the LID from a 138 mm-24 h storm monitored on June 6, 2017.

This confirmed our design principal of mitigating site flooding by runoff peaks shifting, not relaying on storage. However, this important characteristic often is ignored by designers, part of the reason is because the most used EPA (Environmental Protection Agency) SWMM model cannot adequately model it [25]. In most cases the street and community floods are caused by 15-30 min intensive rainfalls, while most drainage systems were designed to convey 1 to 3-year storm events. They are not capable of collecting and conveying the short time intensive storms. Therefore, using GI to collect, infiltrate, store, and delay peaks of runoff at the source can dramatically increase the capacity of drainage systems without enlarging drainage pipes.

The real test for the flood resiliency of the GI facilities came from the Typhoon In-fa. It was a very large and damaging tropical cyclone in 2021 that dropped down 201 mm rainfall to the area. Many city streets and communities without GI were quickly flooded. But the Riverside New Village and other communities renovated using GI were not flooded. Fig. 9 showed that the storm started at the midnight of Sept. 27, 2021. At about 7:00 am next morning, the cumulative rainfall was 95.8 mm. The low-left photo taken around 8:00 am showed little water still ponded in the rain garden. At about 6:00 pm, the rainfall intensity reached the maximum of 76.7 mm/h. The streets outside the community were flooded, but the community was not flooded. The photo taken about 2.5 h later showed that the ground was almost dried out. This indicated that the bioretention and permeable pavement performed well after one year of project completion. The infiltration rate of the bioretention

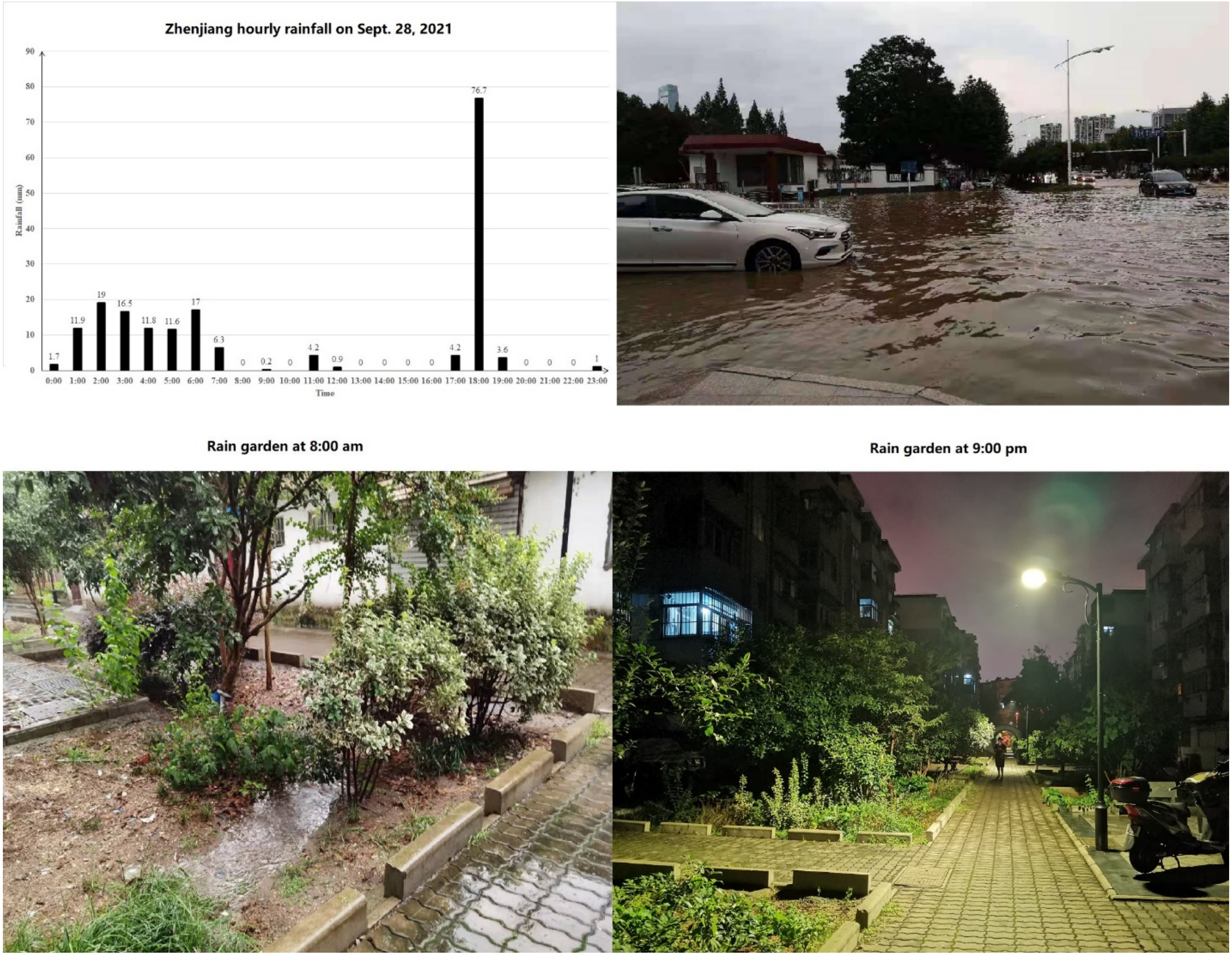


Fig. 9 The performance of the rain gardens and permeable pavement during Typhoon In-fa.

soil was still the same or better as specified and tested in the design and construction phases. To check the validity of the design, the 1-min interval rainfall data collected in the nearby rain gauge were input into the previously built hydrology model. The simulation showed that only two locations identified before had ponding water, but none of them exceeded the flooding standard in China.

Other environmental benefits are also observed. For example, mosquitos in the community have been reduced dramatically because no standing water was present. The community is now a livable and enjoyable place to live. Residents can finally enjoy open spaces for recreation and socialization, for example, playing poker and chess under the shadow of trees. Children are enjoying their new playground as well. Newly created parking lots now allow young people to visit their parents often.

The key findings in the retrospective study include: from the beginning of the design keeping flood control in mind and mimicking sites' hydrologic processes as closer as possible to the predevelopment; outreaching to residences for maintenance issues and resolving conflicts among all parties in good faith; and monitoring the performance of LID facilities continuously; technically, testing the infiltration rate of the native soil prior to the LID design; specifying higher infiltration bioretention soil with the infiltration rate greater than 150 mm/h and 80 mm/h in long and short term, respectively, for permeable pavement choosing PICP to avoid clogging and to keep maintenance cost low.

In 21st century billions of dollars have been invested in GI. Although many cities have incorporated GI into their urban resilient planning, few of them have considered pluvial flood mitigation. For example, New York City has been relatively forward-thinking when it comes to preparing for floods. For years, the city put in more GIs such as permeable pavement, green roof, rain gardens, bioswales and cisterns citywide, and upgraded pumps and drainage pipes in problem areas. These improvements intensified after Hurricane Sandy. But when Hurricane Ida dumped inches of water all over the city in a short time, these GIs were so vulnerable and did nothing to mitigate pluvial flood. By contrast, the GI in Zhenjiang played an important role when Typhoon In-fa dumped similar amount of water over the city. The rainfall intensity of Ida and In-fa is similar too. The maximum hourly rainfall is 80 mm and 76.8 mm for Ida and In-fa, respectively. The different performance of GI during extreme storm events between New York City and Zhenjiang may attribute to the difference in design criteria (WQv vs. LID). According to New York City stormwater resiliency plan the GI is required to manage 1.5 inches of rainfall (38.1 mm) [26], while Zhenjiang applied LID principal and practice for GI design and construction. Therefore, it is urgent to take a comprehensive approach in GI planning, engineering design and practice for pluvial flood resiliency and water quality control.

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