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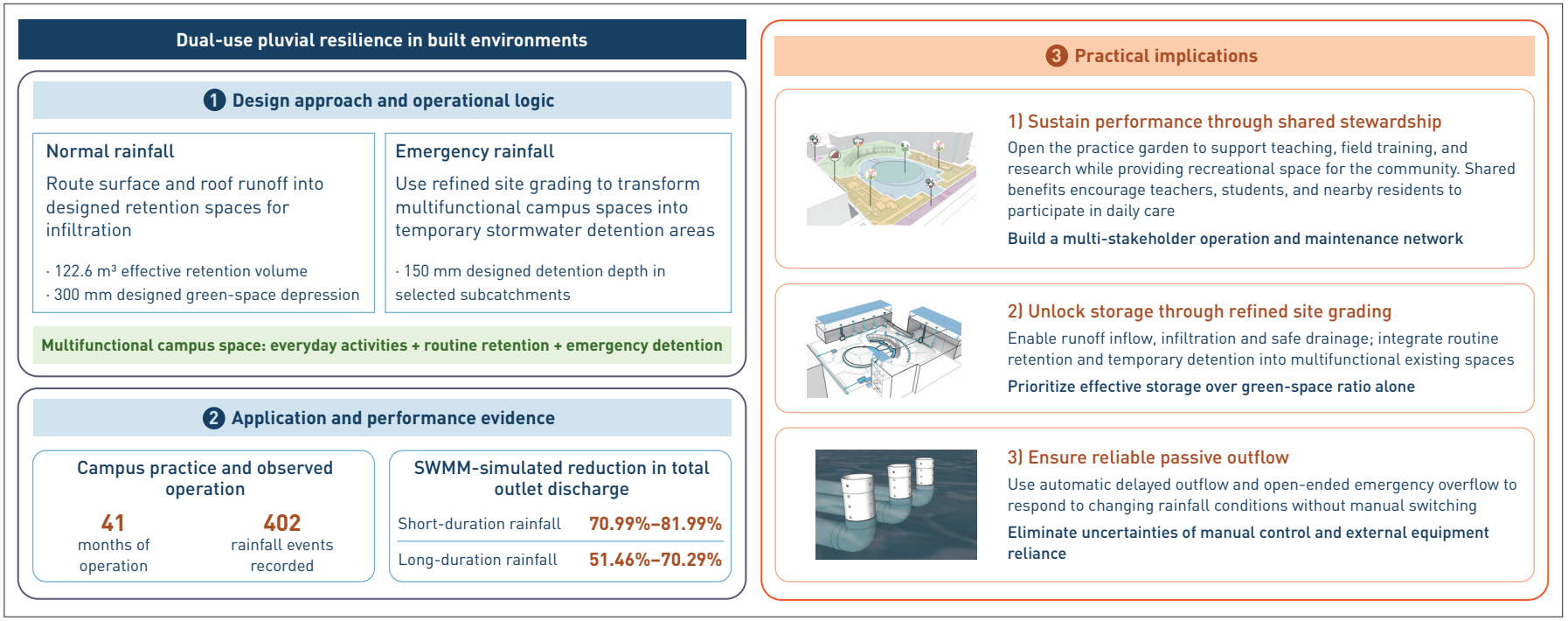
Dual-Use Campus Research and Design for Pluvial Resilience in Normal and Emergency Situations

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GRAPHICAL ABSTRACT



ABSTRACT

Extreme weather and climate events have emerged as major challenges to the sustainable development of human society. Stormwater management in Chinese cities faces complex, systemic challenges. Using the conversion of underutilized campus space into a teaching and training site as a case study, this paper explores approaches to building pluvial resilience featuring dual-use for both normal and emergency situations within built environments. First, functional zoning of the site follows the principles of spatial openness and functional sharing. Mutual benefits for stakeholders foster a stable, collaborative social network for site operation and maintenance, which guarantees the long-term effectiveness of stormwater management. Second, the volumetric method sizes retention spaces for routine rainfall, and coordinated site grading creates temporary detention spaces for emergency rainfall, with their combination forming dual-use stormwater storage. Finally, at the runoff convergence outlet, the design accommodates transitions between normal and emergency rainfall conditions without a fixed operational threshold. Automatic delayed outflow without manual intervention ensures reliable and safe temporary rainwater storage and emergency overflow. Having operated for 41 months, the site has experienced 402 rainfall events of different intensities and achieved favorable pluvial flood control outcomes. Based on the

renovation of existing campus space, this study establishes a model of dual-use pluvial resilience, offering a practical example for stormwater management and multifunctional use within the urban built environment.

KEYWORDS

Dual-Use; Pluvial Resilience; Retention Detention Space; Site Grading; SWMM; Delayed Outflow; Sponge City; Open Space

HIGHLIGHTS

- Over 41 months, the garden managed 402 rainfall events with sound stormwater management performance
- Spatial openness and functional sharing support multi-stakeholder site operation and maintenance
- Automatic delayed outflow enables retention, detention, and emergency overflow without manual control

RESEARCH FUND

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1 Introduction

The World Climate Research Programme (WCRP) identified understanding and predicting weather and climate extremes as one of its seven Grand Challenges. Between 2000 and 2022, 209 recorded extreme flood disasters worldwide ranked first among all climate extremes[1]. In 2024, 64.8% of China's total natural disaster losses stemmed from floods[2], with direct economic losses equivalent to 0.19% of the national gross domestic product (GDP)[3]. By contrast, the GDP share of stormwater-induced economic losses in Japan during 2010–2020 was less than half that of China[4]. In recent years, frequent severe pluvial floods in China have exposed critical weaknesses in coping with extreme rainfall exacerbated by climate change. These challenges arise partly from the compact human settlements within China's urban built environments, combined with rainfall patterns associated with the monsoon climate. They also stem from the long absence of unified urban waterlogging prevention standards[5], segregated fluvial and pluvial flood governance[6], and fragmented institutional arrangements: parallel standards for urban drainage[7], pluvial flooding prevention[8], and fluvial flooding control[9] are managed by different authorities using distinct calculation methodologies. As Chinese cities shift from urban expansion to qualitative development, built environments serve not only as primary sites for urban regeneration, but also as areas of concentrated stormwater management challenges. Can the stormwater management capacity of built-up areas be improved without upgrading underground drainage networks? How can a framework for managing rainfall of different magnitudes build on conventional coping strategies for moderate and light rainfall? How can pluvial resilience be sustained while developing sustainable operation and maintenance mechanisms? These are pressing practical challenges. By examining common challenges in stormwater management within Chinese cities, and considering that university campuses are representative samples of urban built environments—featuring single land ownership, a high proportion of public space, and concentrated, regular human activities—this study selects a renewal project of existing campus space as the research case. It explores approaches to building pluvial resilience through multifunctional site use, aiming to provide a design framework for similar projects.

2 Pluvial Management Challenges for Urban Built Environments

2.1 Adaptation Challenges Under Monsoonal Rainfall

China's territory is largely dominated by monsoon circulation, and most cities exhibit monsoonal rainfall features marked by pronounced variation in rainfall between months. Taking Changsha, which has a humid subtropical monsoon climate, as a case study, daily rainfall records from January 1, 1987 to December 31, 2024 were compiled from datasets provided by the National Centers for Environmental Information of the National Oceanic and Atmospheric Administration (NOAA). Statistics show that the average annual rainfall reaches 1,477.83 mm, with distinct patterns: precipitation in the wettest months of May (209 mm) and June (236 mm) is approximately four and five times that of December, the driest month (47 mm), respectively. Light to moderate rainfall[10] occurs frequently but contributes a small share of total rainfall, while rainstorms and heavier events occur infrequently yet make up a large share of total rainfall (Fig. 1). *The Technical Guide for Sponge City Construction: Construction of Low-Impact-Development Stormwater Systems (Trial)*[11] (the "Guide" hereafter) defines the volume capture ratio of annual rainfall (VCRAR) as the core metric of urban stormwater

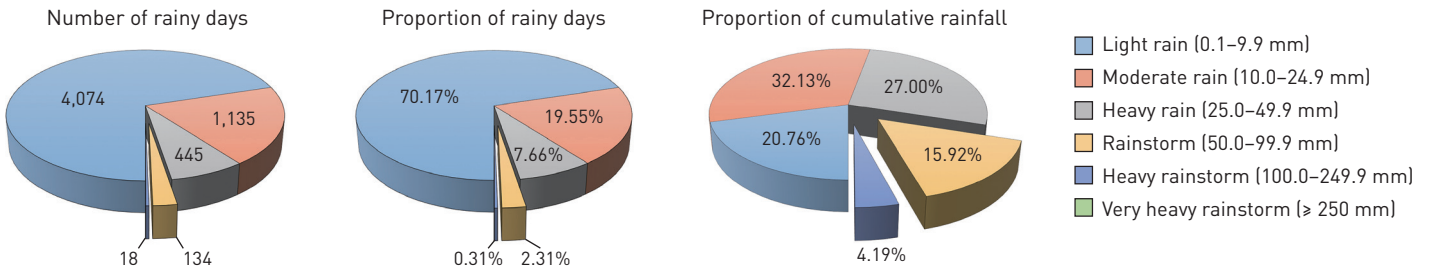
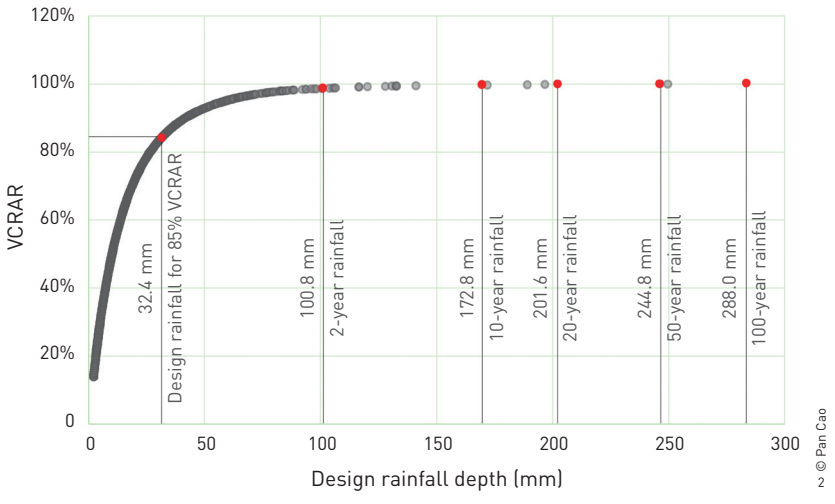


Fig. 1 Rainfall statistics by precipitation grade in Changsha based on long-term daily rainfall records.

management. Derived from long-term daily rainfall statistics, this indicator is used to assess the proportion of runoff retained onsite. The volume (V) of retention facilities is determined by the volumetric method ($V = 10H\varphi F$), using design rainfall depth (H), catchment area (F), and runoff coefficient (φ)[11]. Frequency analysis based on 38 years of rainfall data for Changsha yields the curve of VCRAR and design rainfall depth (Fig. 2). At the 85% target, the corresponding depth is 32.4 mm. The volume captured under this target amounts to only 32.14%, 18.75%, 16.07%, 13.24%, and 11.25% of the runoff volumes generated by long-duration (24 h) rainfall events with return periods of 2 yr, 10 yr, 20 yr, 50 yr, and 100 yr, respectively. For monsoonal rainfall cities represented by Changsha, there is a substantial gap between the planned retention space for sponge city practices and the required detention space under high-intensity rainfall. Municipal drainage networks with fixed capacity ceilings may also be overwhelmed by highly concentrated extreme rainfall. One way to address this challenge is developing pluvial resilience strategies that address both the routine pressure from normal-condition rainfall (high frequency, low volume) and the abrupt shocks from emergency-condition rainfall (low frequency, large volume).

Fig. 2 Comparison of the VCRAR curve and design rainfall depths for different return periods under long-duration rainfall in Changsha.



2.2 Implementation Challenges for Dual-Use Pluvial Practices

The concept of dual-use for normal and emergency situations builds on the integration of peacetime and wartime functions, routine and disaster-response functions, and routine and epidemic-response functions. It aims to integrate normal and emergency functions in public infrastructure development, balancing urban economic development and urban disaster resilience[12]. Attention to the multi-functionality of urban detention and retention facilities within drainage systems[13–14], together with calls for the integration of urban green spaces as stormwater management infrastructure[15], has brought this concept to urban pluvial management[16–17]. Accordingly, dual-use pluvial practices refer to new construction or renovation of urban public spaces to balance regular site functions, capture normal-condition runoff and temporarily detain runoff from rainfall exceeding the design threshold within retention and detention spaces respectively. Such practices cover planning, design, construction, and operation and maintenance.

Theoretically, dual-use pluvial resilience can be achieved via real-time control (RTC) to optimize spatial allocation. However, practical implementation involves far more considerations than idealized conditions. First, real-world settings are more complex than conceptualized models: offline monitoring data reveal that the runoff actually regulated by site-scale stormwater systems can exceed three times the value predicted by hydrological models[18]. Online monitoring indicates that micro-watershed boundaries shift as rainfall rises; canopy interception varies with rainfall following an approximately logarithmic relationship[19]. Over time, infiltration rates in vegetated areas may increase[20]. Second, cross-dimensional implementation barriers limit performance. Key factors shaping dual-use development include prior flood experience, awareness of construction proposals, and stakeholder interests[21]. Ambiguous management rules and responsibilities create practical hurdles for multi-functional stormwater facilities during function switching[22]. Clear timelines, defined duties, and measurable targets are indispensable for pluvial resilience design[23–24]. Long-term research from communities in Scotland[25]

highlights the value of participatory and collaborative flood risk management. Cross-departmental coordination and community incentive strategies[26] also validate the effectiveness of public engagement. Furthermore, securing long-term stable performance of stormwater management and mitigating the risk of facility abandonment pose another practical challenge.

While overseas cities have undertaken early explorations of dual-use urban pluvial solutions[25,27–28], related research and practice in China started later and remain limited[29]. As of 2026, at the urban planning level, only the *Special Plan for Resilient Urban Space of Beijing (2022–2035)* and the *Resilience Improvement Plan and Action Plan for Beijing Sub-Center* address this topic[30]. Among current codes and guidelines, only the *Planning and Design Guideline for Dual-Use Stormwater Retention and Detention Facilities in Shanghai* describes the classification and design considerations for such facilities[16]. Wenliang Wang's construction of detention basins, achieved via optimized basin geometry and hydraulic calculations, stands among the few implemented dual use pluvial applications[31]. Urban pluvial flooding arises from complex causal mechanisms. Drainage networks planned with a narrow, site-only perspective carry substantial risks of major failure. External inflow and backflow at pipe junctions may create bottlenecks within the overall drainage system[32]. Short-duration heavy rainfall also exacerbates flood risks within small catchments[33]. Although the Guide proposes a hierarchical governance framework of "source reduction, combined storage and drainage, flood drainage and hazard mitigation, and emergency response under over-limit conditions," practical implementation focuses primarily on low-impact development facilities[34]. These inherent limitations, compounded by insufficient unified standards and disjointed management of pluvial and fluvial floods in China, make it difficult to establish adaptive pluvial risk criteria and response strategies for variable rainfall magnitudes.

3 Campus Design Practice

As an integral component of the urban built environment, university campuses share interconnected topography, vertical gradients, and drainage networks with surrounding urban areas. A growing number of landscape performance cases for campus stormwater management have emerged[18], rendering campuses ideal testbeds for developing innovative urban pluvial resilience strategies. To support professional teaching, Changsha University of Science & Technology (CSUST) built a landscape architecture field teaching base, namely the Practice-Base Garden. Construction of this garden began in August 2022; it was completed and opened in November of the same year and remains operational.

3.1 Project Overview and Design Requirements

The site lies to the north of Chiling Road, on the highest ground of the Jinpenling Campus of CSUST in Tianxin District, Changsha, Hunan Province. The campus was formed from two universities founded in the 1950s, with ageing infrastructure. Covering a design area of 4,695.7 m^2, the site is enclosed by the Comprehensive Teaching Building, Hydraulic Experiment Building and Harbour–Navigation Center. The three buildings feature internal roof drainage. The terrain is generally flat; surface runoff flows along an east–west axis into the open ditches on the northern and southern sides. The site mainly comprises lawns, shrubs, paved surfaces, and a small number of trees, alongside a curved pavilion corridor (Fig. 3). Lacking functional and spatial variety, the site sees minimal visitation and exemplifies typical underutilized existing space. Given its long service life, complete baseline records were unavailable. Topographic surveys were conducted using a levelling instrument, and the study team reviewed as-built drawings of surrounding buildings archived by the university to map the pre-construction site layout and surrounding drainage pipe network details (see details in Supplementary Material). Consistent with many ageing urban built-up areas, the site suffers from combined sewer inflow and pipe damage. A large septic tank from the northern teaching building discharges into the storm pipe, creating risks of rainfall-driven sewage overflow.

The project is designed as an open campus space. It fulfils practical teaching demands including observation, recognition, field investigation, surveying, hands-on training, and site management. It also meets the broader demand for a better campus setting and outdoor activities for staff and students. Furthermore, the aim



Fig. 3 Original site conditions before construction.

is to develop and maintain the site as a living teaching resource addressing urban pluvial challenges while supporting public activity.

3.2 Framework for Site Pluvial Resilience

3.2.1 Multi-Stakeholder Shared Functional Zoning

The Practice-Base Garden is the third garden project developed by the authors' team, following the first Kids' Garden at Hunan Agricultural University[35] and the second Kids' Garden at Yucai No. 3 Primary School[36]. Experience from the two previous projects indicates that developing an effective long-term maintenance mechanism is vital to realizing the actual benefits of the site. In delineating functional zones, the design combines site conditions and design requirements and, for the first time in this series of projects, incorporates course-based practical requirements into the spatial layout. Guided by an open and shared strategy, the site is divided into several main functional zones: public activity zone, learning and exchange zone, construction training zone, and ecological experiment zone. The public activity zone occupies the site center, consisting of a gently sloped lawn and circular plaza. It serves as the primary leisure and exercise space for staff, students, and nearby residents. The learning and exchange zone lies on the west side, fitted with wood-plastic decks, gravel plazas, and the existing pavilion corridor. A shade-tolerant garden is created beneath mature evergreen trees for shade-loving plant cultivation. Sited on the northern and southern sides with ample sunlight, the construction training zone functions as a sun-loving garden. It supports the cultivation and identification of heliophytes while forming an attractive landscape. The ecological experiment zone comprises two components. The southwest corner contains an ecological pond with vegetated gentle slopes for biodiversity observation and aquatic ecology experiments. The eastern segment contains a bioretention swale that captures stormwater and acts as an experimental plot for plants and soils associated with rain gardens. This zoning balances functional demands of core professional courses and campus outdoor recreational needs. Instead of following the typical closed model for teaching bases, the Practice-Base Garden operates through spatial openness and shared functions. It supports multiple demands of staff, students, and residents for teaching, research, gathering, recreation, and exercise (Fig. 4). The site thus draws wide attention, creating conditions to foster a multi-stakeholder collaborative network and underpin the long-term performance of dual-use pluvial resilience.

3.2.2 Layout of Storage Spaces for Normal and Emergency Conditions

Runoff pathways are designed in the Practice-Base Garden following terrain features. With gravity-driven runoff routing and pipe connections, roof and surface runoff are integrated into site storage spaces to form a concealed conveyance network (Fig. 5). Diverse retention spaces are developed for teaching and research needs, and refined site grading ensures rainwater can flow into these spaces. A double-ring infiltrometer test was conducted on site soils, yielding a measured infiltration rate of 3.05×10^{-6} m/s. Accordingly, a depression depth of 300 mm was adopted for the sunken green space to ensure full infiltration of incoming runoff within 24 h. For normal-condition rainfall events, the design uses Changsha's curve of VCRAR and design rainfall depth, with the 85% VCRAR defined as the management target. This generates an effective retention volume of approximately 122.6 m^3 (Fig. 6). Calculated via the volumetric method specified in the Guide, the site yields an 89.9% VCRAR,

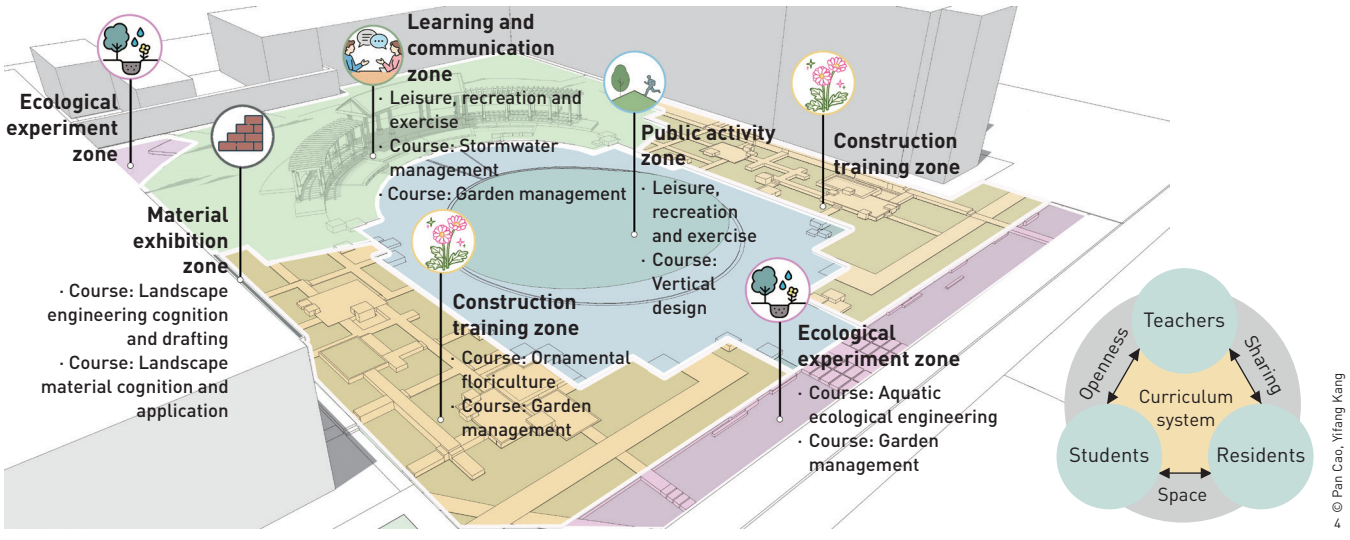
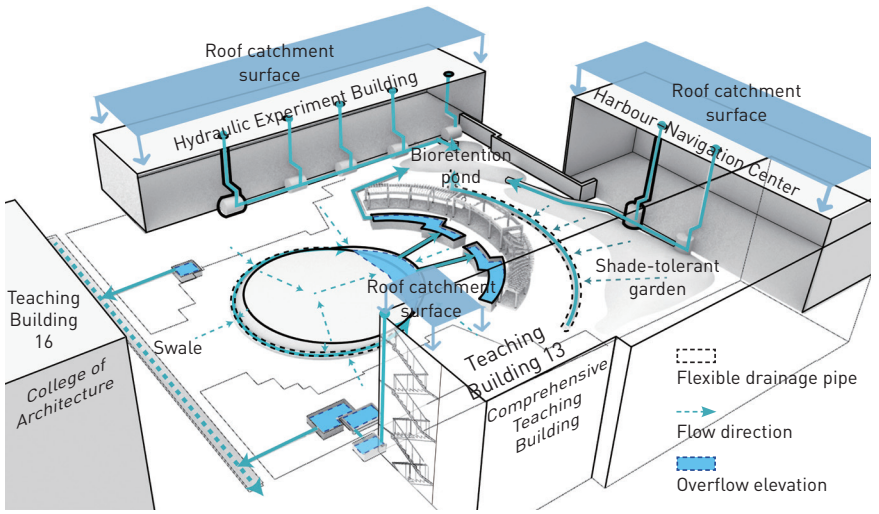
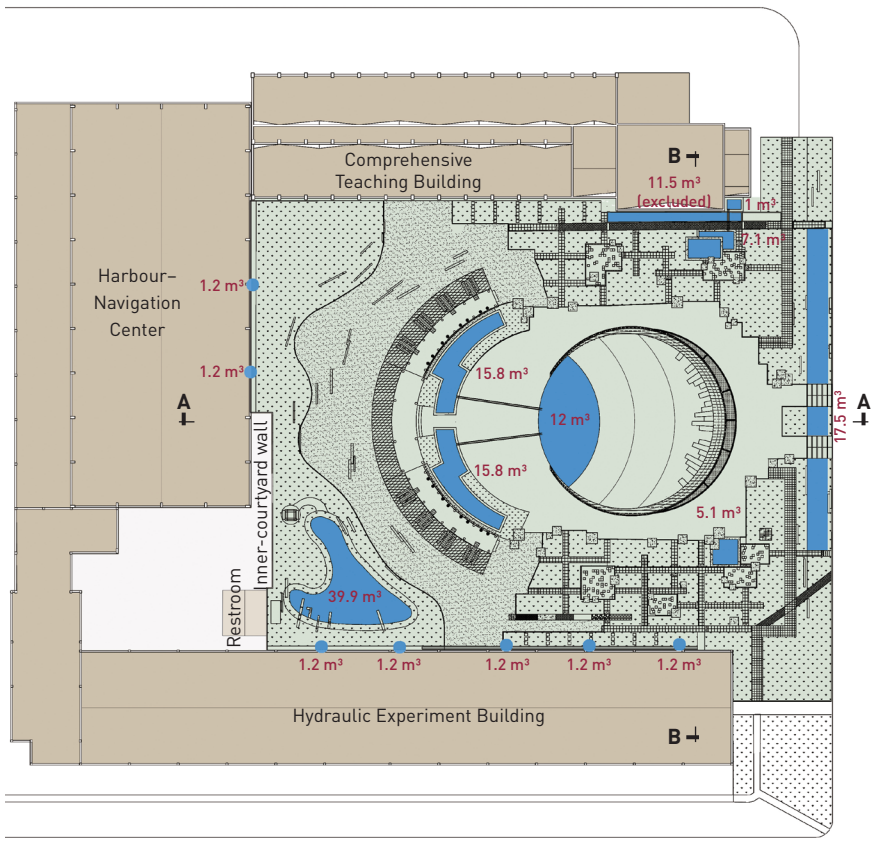


Fig. 4 Shared spaces among multiple stakeholders within the functional zoning of the Practice-Base Garden.



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Fig. 5 Schematic diagram of stormwater runoff pathways in the Practice-Base Garden.

Fig. 6 Distribution of stormwater retention spaces for normal–condition rainfall in the Practice-Base Garden.

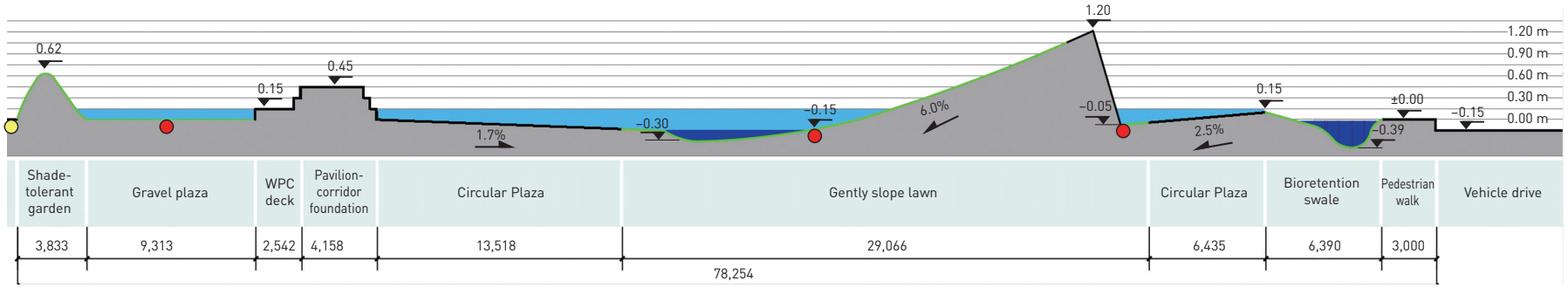
which can effectively cope with normal-condition rainfall events with a daily rainfall depth of no more than 40.6 mm.

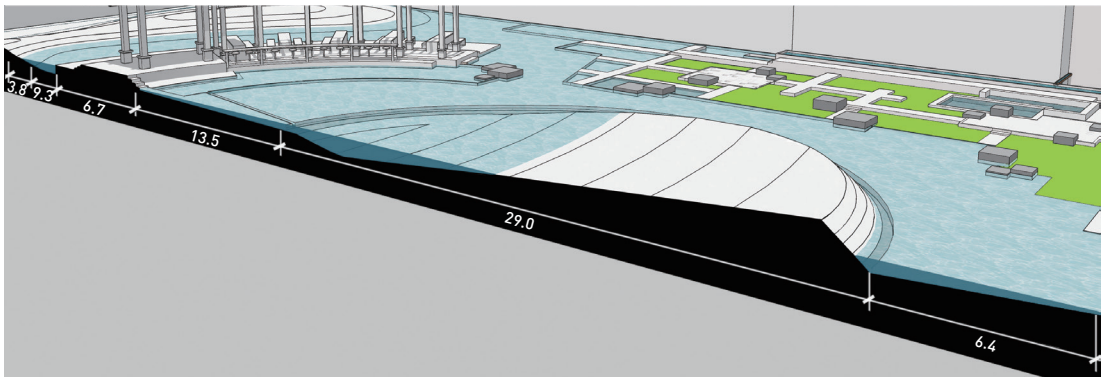
Retention spaces for normal-condition rainfall are inadequate for rainstorms and heavier rainfall events. Under Changsha's monsoon climate, such heavy rains occur rarely yet contribute a large proportion of total annual rainfall. To address this issue, detailed site-grading strategies are implemented: The Circular Plaza encircles the gentle-slope lawn. This impervious plaza is graded with high outer edges and low inner edges to form an inward slope for runoff conveyance, and permeable underdrains are laid along the lawn's outer perimeter to divert runoff. The shade-tolerant garden uses micro-topography to avoid plant waterlogging and enrich spatial enclosure. The wood-plastic deck is built upon the existing concrete platform, with its finished surface 150 mm above the gravel plaza. The pavilion-corridor foundation and shade-tolerant garden micro-topography act as retaining barriers, enabling the gravel plaza to hold extra stormwater; runoff flows via flexible permeable hoses under gravel to the southwest ecological pond (Fig. 7). The sun-loving garden adopts raised planting beds. Beyond its teaching and research function for cultivating heliophytes, this design creates a layered public landscape. Elevated beds prevent root waterlogging and, together with the inward-sloping Circular Plaza, grant the area capacity for temporary stormwater detention (Fig. 8). These targeted designs unlock extra stormwater detention capacity within the public activity, learning and exchange, and construction training zones while preserving their primary functions. This enables the site to cope with emergency-condition rainfall exceeding the standards specified in the Guide. Together with the aforementioned retention spaces for normal-condition rainfall, these multi-functional areas constitute dual-use pluvial spaces.

3.2.3 Design for Transition Between Normal and Emergency Conditions

The suddenness and uncertainty of rainfall make defining a threshold between normal and emergency conditions a major challenge for dual-use systems. This creates practical barriers to real-time transition between the two states, and poses difficulties for RTC technology, which relies heavily on power supply and accurate weather forecasting. Seamless transition between scenarios is critical to realizing the benefits of dual-use pluvial resilience and securing site safety. The project employs an automatic delayed outflow design to tackle this issue.

Based on the site's original elevation, the pre-construction catchment was divided into four subcatchments S_1, S_2, S_3 and S_4, each connected to the municipal drainage network via outlets O_1, O_2, O_3, and O_4, respectively. Firstly, refined site grading (see Supplementary Material) restructured the original catchment boundaries: runoff originally discharged through O_3 was reduced to mitigate sewage overflow risks on the northern site. Surface runoff from within the design area and roof runoff diverted from outside

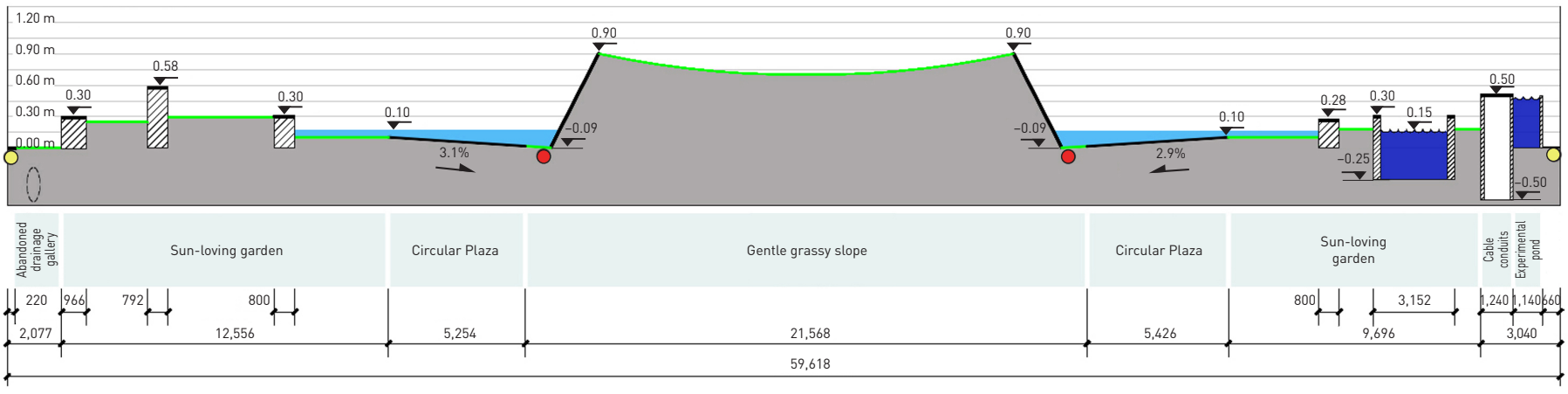


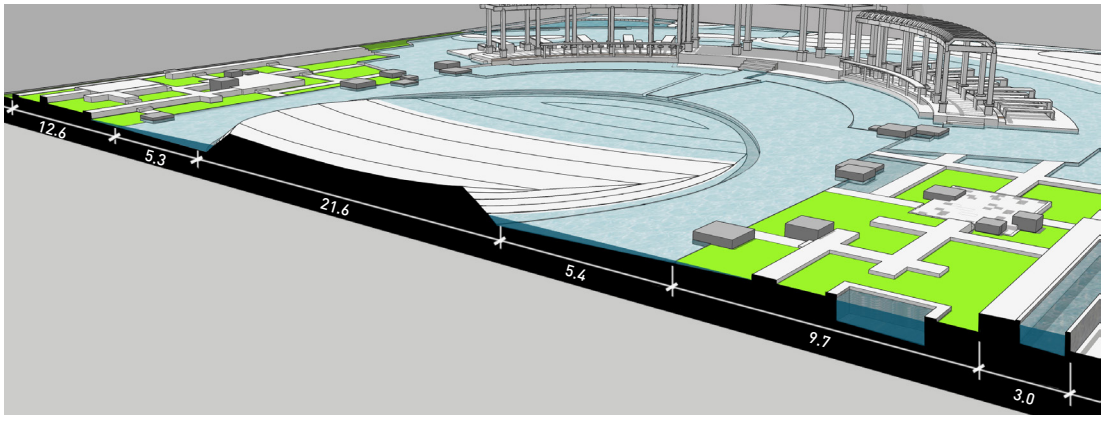


Retention space under normal-condition rainfall
Detention space under emergency-condition rainfall
Pervious surface
Impervious surface
Open drain
Flexible drainage pipe

NOTE: Dimensions are in mm (upper section) and m (lower schematic section). The vertical scale of the standard section is exaggerated by a factor of 4 relative to the horizontal scale.

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Retention space under normal-condition rainfall
Detention space under emergency-condition rainfall
Pervious surface
Impervious surface
Open drain
Flexible drainage pipe

NOTE: Dimensions are in mm (upper section) and m (lower schematic section). The vertical scale of the standard section is exaggerated by a factor of 4 relative to the horizontal scale.

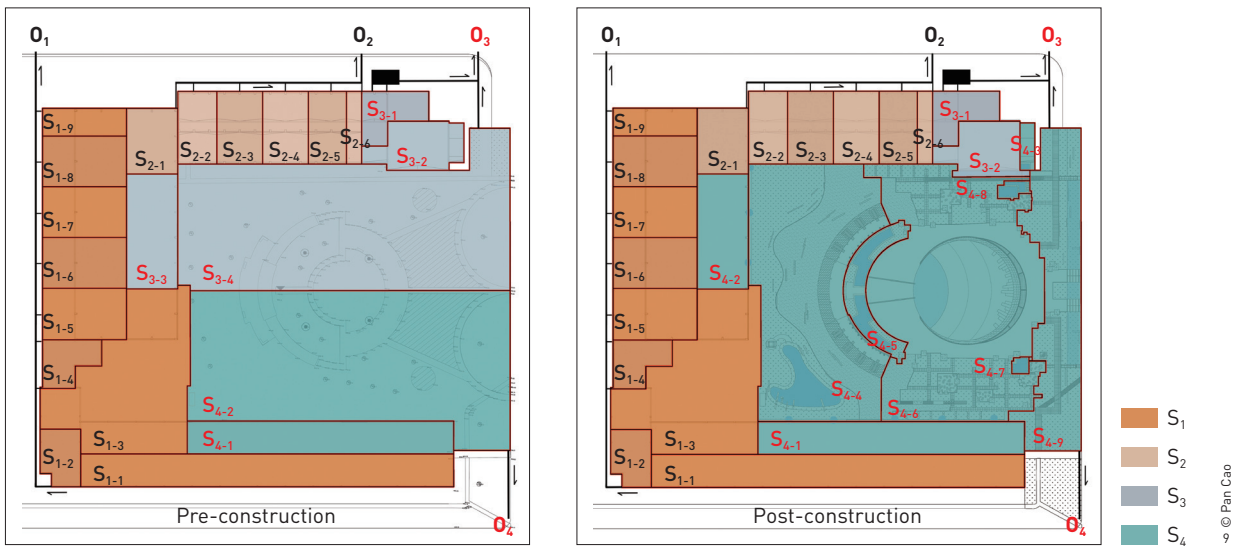
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Fig. 7 Section A–A of the Practice-Base Garden and schematic illustration of stormwater detention.
Fig. 8 Section B–B of the Practice-Base Garden and schematic illustration of stormwater detention.

it through downspout disconnection were integrated into the new subcatchment S_4. Following this design, subcatchments $S_{4\text{-}1}$, $S_{4\text{-}2}$, $S_{4\text{-}3}$, $S_{4\text{-}4}$, $S_{4\text{-}5}$, and $S_{4\text{-}6}$ drain into an ecological pond as their terminal. An additional drainage pipe routes overflow to the abandoned drainage gallery, enabling connection to the municipal drainage system (Fig. 9). Considering prior design and site conditions, a 150 mm depth was defined for temporary stormwater detention in $S_{4\text{-}4}$, $S_{4\text{-}5}$, and $S_{4\text{-}6}$. Secondly, calculations using weir and orifice equations[37], calibrated against observed rainfall events, guided the installation of three DN110 polyvinyl chloride (PVC) pipes at the overflow outlet as site emergency overflow channels. The overflow pipe's inlet rim sits 150 mm above the normal retention elevation of the ecological pond. The open ends ensure free discharge for rainfall beyond the set maximum depth. Sixteen holes of 10 mm diameter were drilled into the section of each pipe above the normal retention elevation to create automatic delayed outflow orifices (Fig. 10). Refined site grading coordinates retention spaces, detention spaces, and runoff pathways, coupled with natural infiltration over gravel plazas and gentle-slope lawns, it produces the site's automatic delayed outflow. This design blurs the threshold between normal- and emergency-condition rainfall scenarios and removes uncertainties from manual operation and external equipment reliance.

4 Assessment of Project Performance

Commissioned in November 2022, the Practice-Base garden has been in continuous operation for 41 months as of 10 May 2026. Rainfall data were measured by the mini weather station installed within the garden at a 10-minute time step.Classified by daily rainfall depth, 402 rainfall events were recorded: 268 light rainfall events, 78 moderate rainfall events, 34 heavy rainfall events, 18 rainstorms, and 4 heavy rainstorms.



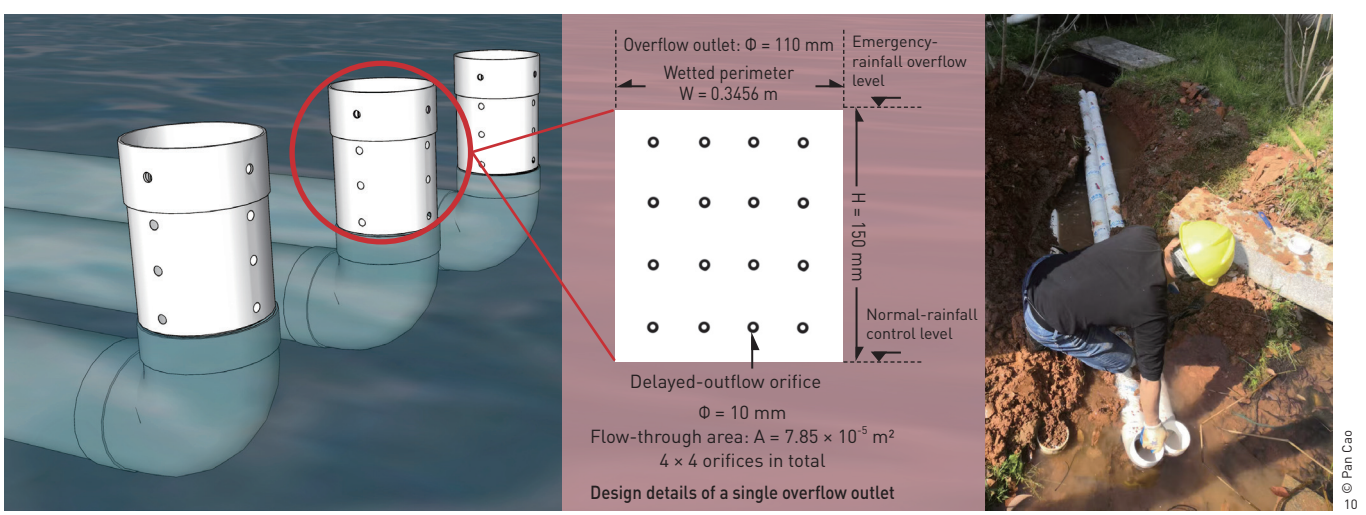


Fig. 9 Comparison of site subcatchment delineation and outlet locations before and after construction. Black labels indicate unchanged subcatchment boundaries and outflow conditions, while red labels indicate changes in both.

Fig. 10 Automatic delayed outflow design and its on-site installation.

4.1 Observed Stormwater Retention and Detention Performance

From 00:00 on 14 April to 00:00 on 15 April 2024, total rainfall of 18.6 mm was recorded, representing a moderate event. A peak rainfall of 11.2 mm occurred at 06:50. Within the retention space of the gentle-slope lawn, runoff collection and infiltration were clearly observed. All captured runoff fully infiltrated by 12:30 (Fig. 11). From 00:00 on 24 June to 00:00 on 25 June of the same year, the site received 188.2 mm of total rainfall, classified as a heavy rainstorm. The maximum 10-minute rainfall depth of 18 mm was recorded from 09:20 to 09:30. Precipitation then continued intermittently until 23:30. The maximum rolling 1-hour cumulative rainfall reached 65.6 mm, the highest hourly value among all measured rainfall events. Runoff detention was observed across the circular plaza, gravel plaza, sun-loving garden, and bioretention swale (Fig. 12). By 16:00 on 25 June, runoff detained in the largest sunken green space had fully infiltrated. Teaching and research activities at the Practice-Base Garden remained uninterrupted that day.

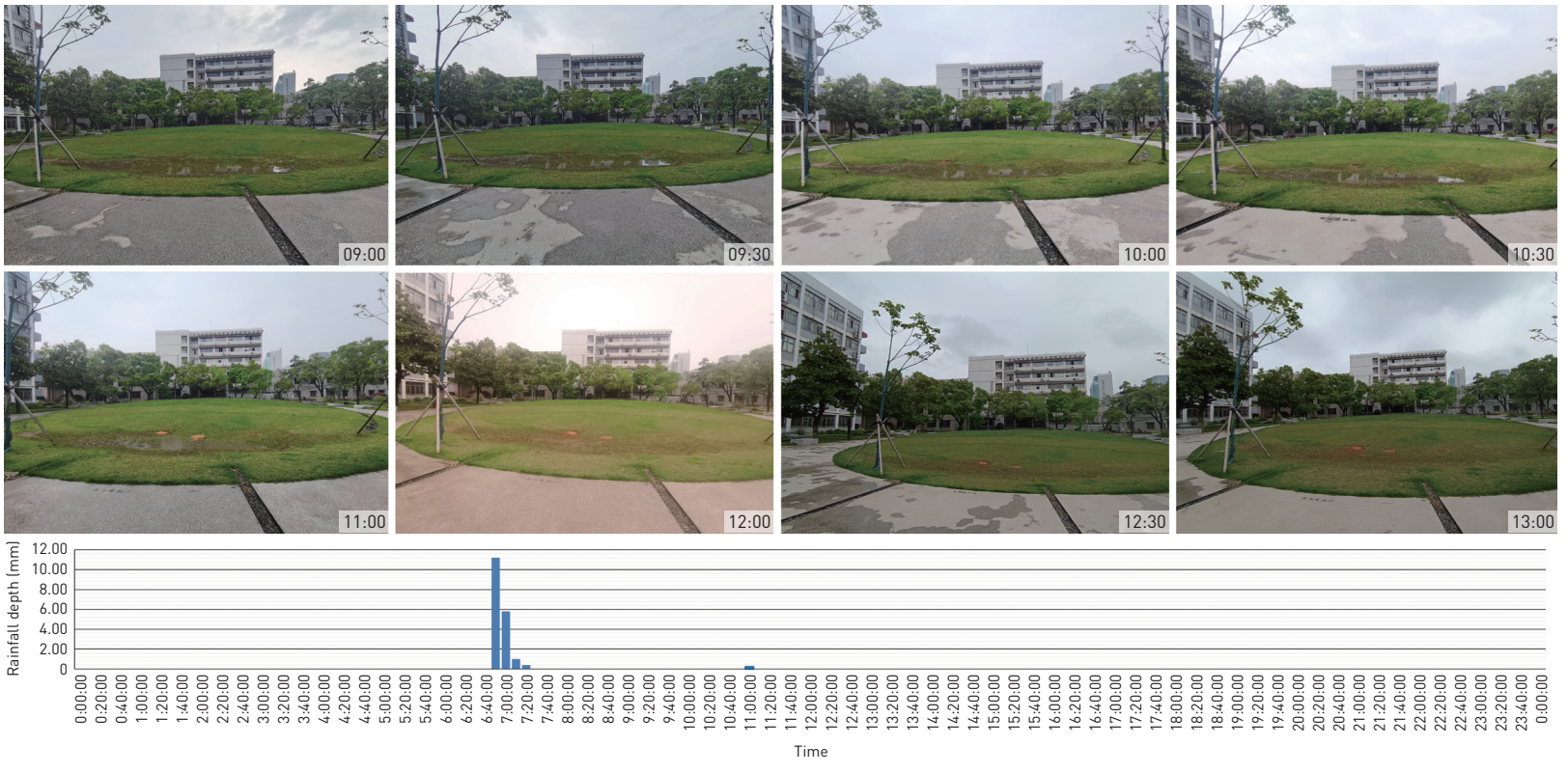
4.2 Hydrological Modelling Assessment of Stormwater Performance

The Storm Water Management Model (SWMM) was used to conduct hydrological modelling for the pre- and post-construction conditions (see Supplementary Material). Parameters were calibrated based on infiltrometer tests, model default values and measured rainfall data (Table 1). Within SWMM, the calibrated depression storage depths for impervious (Dstor-Imperv) and pervious areas (Dstor-Perv) were set to 151 mm and 155 mm, respectively, serving as generalized parameters to represent the 150 mm temporary detention capacity of subcatchments $S_{4\text{-}4}$, $S_{4\text{-}5}$ and $S_{4\text{-}6}$ under the post-construction scenario. The rainfall dataset officially issued by Municipal Bureau of Housing and Urban-Rural Development and Municipal Meteorological Bureau of Changsha was adopted for the simulation[38]. Short-duration rainfall hyetographs (120 min, 1 min time step) were derived from:

$$q = \begin{cases} \dfrac{3424.84(1 + 0.8185 \lg P)}{(t + 21.299)^{0.8195}}, & 2 \le P \le 10\,\text{yr}, \\ \dfrac{13931.34(1 + 0.5136 \lg P)}{(t + 37.869)^{1.04}}, & P > 10\,\text{yr} \end{cases}, \tag{1}$$

where q is the design rainfall intensity [L/(s·hm^2)], t is the rainfall duration (min), and P is the design return period (yr);whereas long-duration hyetographs (1,440 min, 5 min time step) were generated by the same-frequency method. Hyetographs of short and long durations for return periods of 2 yr, 3 yr, 5 yr, 10 yr, 20 yr, 30 yr, 50 yr, and 100 yr were used to quantify outflow hydrographs

Fig. 11 Observed stormwater retention on the gently sloped lawn during the April 14 rainfall event.



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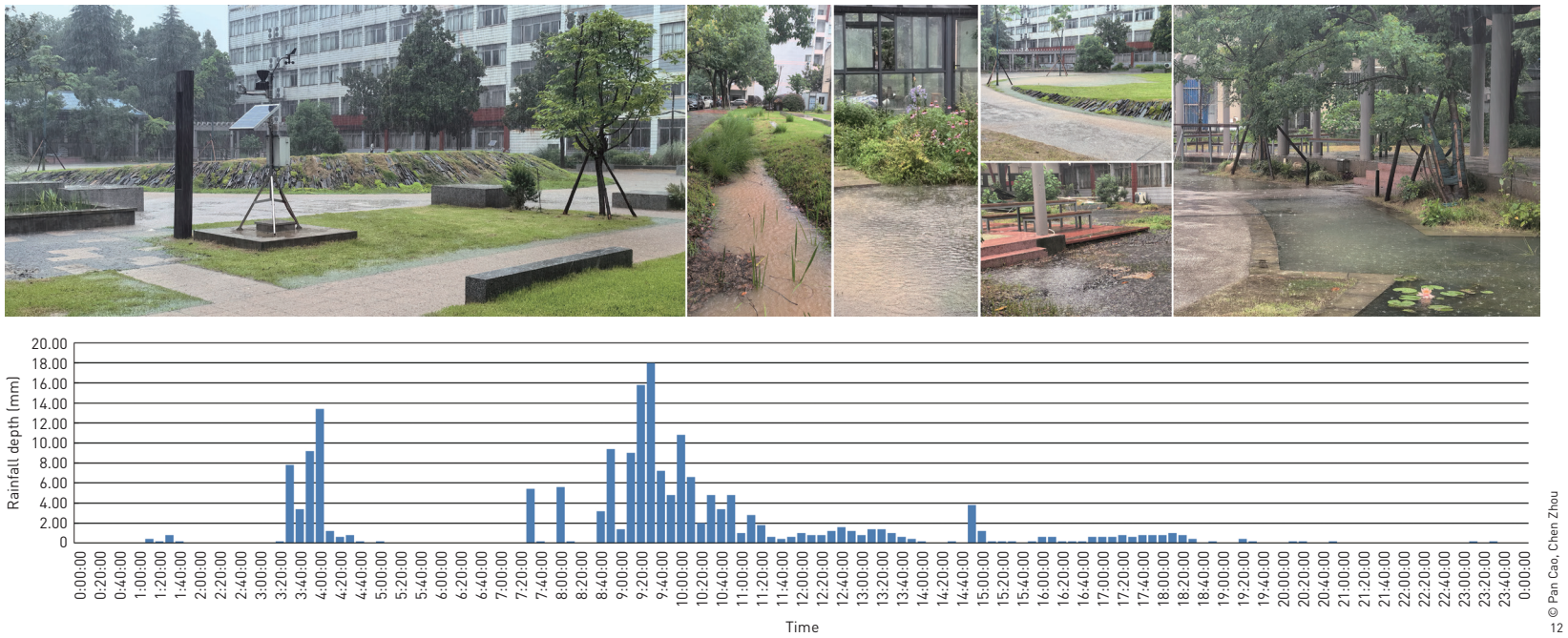


Fig. 12 Observed stormwater detention in the Practice-Base Garden during the June 24 rainfall event.

Table 1: Typical hydraulic parameter values for the Practice-Base Garden model

Parameter (unit)	Roof space	Green surface	Water plaza	Paved plaza	Gravel plaza
Impervious surface roughness coefficient	0.011	0.012	0.011	0.013	0.013
Pervious surface roughness coefficient	0.10	0.15	0.10	0.24	0.24
Impervious depression storage (mm)	0.05	1.00	0.05	1.00	1.00
Pervious depression storage (mm)	0.05	5.00	0.05	5.00	5.00
Proportion of impervious area without depression storage (%)	25	25	25	25	25
Maximum infiltration rate (mm/h)	3	60	3	3	60
Minimum infiltration rate (mm/h)	0.5	1.0	1.0	1.0	1.0
Decay constant (1/h)	4	4	4	4	4
Drainage time (d)	1	5	5	1	5
Infiltration method	Horton				

at outlets O_3 and O_4 under pre- and post-construction scenarios.

Under short-duration rainfall conditions, pre-construction peak outflow at outlet O_3 increased from 30.9 L/s to 50.26 L/s with return periods from 2 yr to 100 yr. At O_4, full-pipe flow occurred at 36.22 L/s for the 3-year return period, and its duration grew from 10 min to 37 min with rising return periods. Post-construction, owing to the re-division of site subcatchments, peak outflow at O_3 rose moderately from 3.99 L/s to 13.78 L/s, while O_4's peak outflow increased from 10.85 L/s to 29.91 L/s across the same range of return periods. All peaks were substantially reduced and full-pipe flow disappeared (Fig. 13). Under short-duration rainfall, the Practice-Base Garden's pluvial resilience design compensates for the inadequate conveyance of the ageing municipal drainage network.

Under long-duration rainfall conditions, pre-construction peak outflow at outlet O_3 increased from 37.45 L/s to 47.81 L/s as return periods rose from 2 yr to 100 yr. At O_4, full-pipe flow occurred at an outflow rate of 36.22 L/s even under the 2-year return period; with rising return periods, the duration of full-pipe flow extended from 10 min to 35 min. Post-construction, full-pipe flow was eliminated. Peak outflow at O_3 was substantially reduced across all return periods, rising from 6.76 L/s to 19.82 L/s. Peak outflow at O_4 increased from 15.02 L/s to 39.46 L/s. For return periods of 20 yr, 30 yr, 50 yr, and 100 yr, the peak outflow at O_4 temporarily exceeded the pre-construction maximum of 36.22 L/s for durations ranging

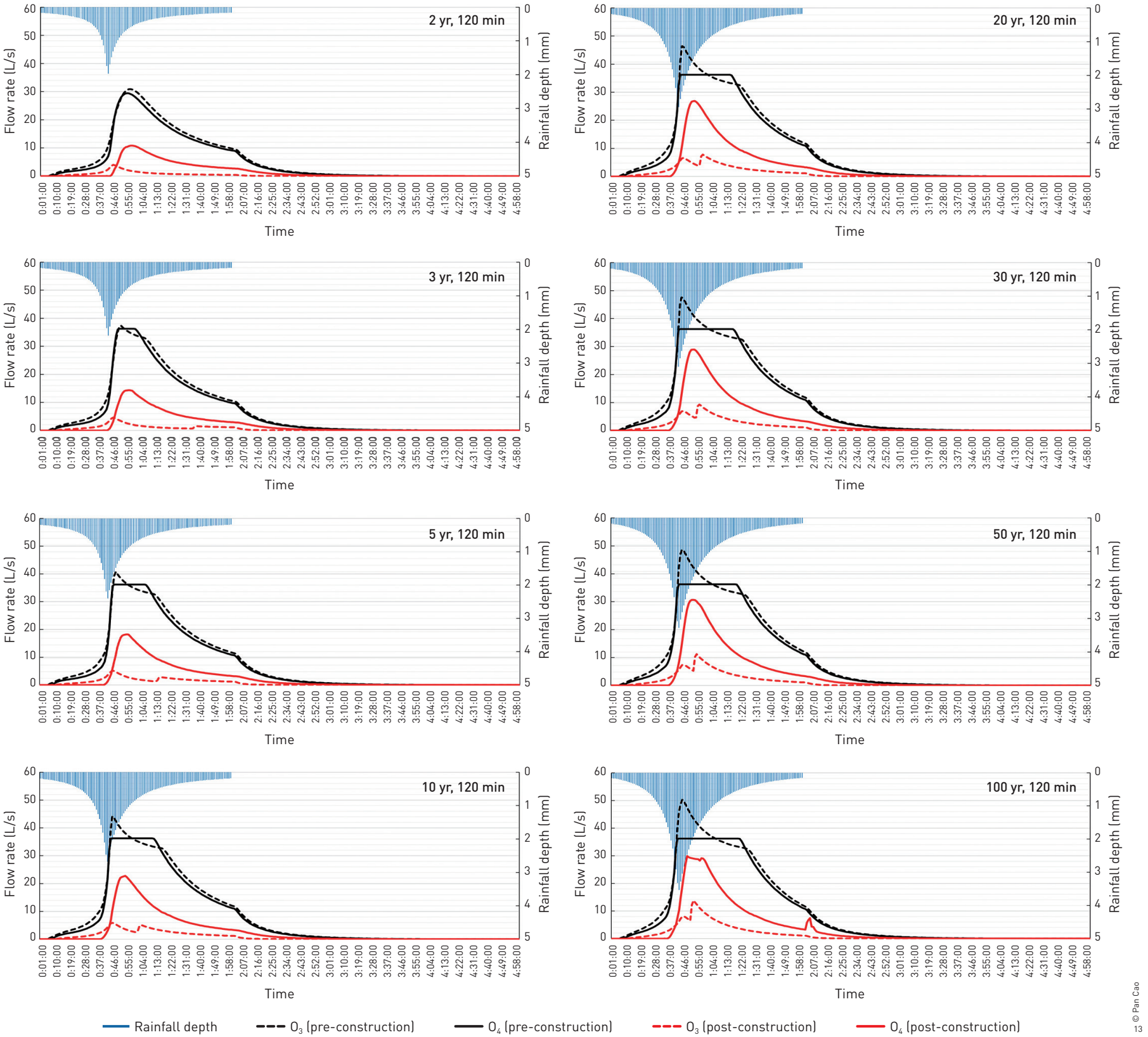


Fig. 13 Outflow hydrographs at outlets O_3 and O_4 before and after construction under short-duration rainfall events.

from 5 min to 15 min, reaching 39.46 L/s, 38.24 L/s, 39.03 L/s and 39.03 L/s, respectively (Fig. 14). Under long-duration rainfall, the on-site ageing drainage network is subject to more severe pluvial stress. While the Practice-Base Garden mitigates its inadequate conveyance capacity, the added detention spaces relieve hydraulic congestion within the original pipelines and lift conveyance limits

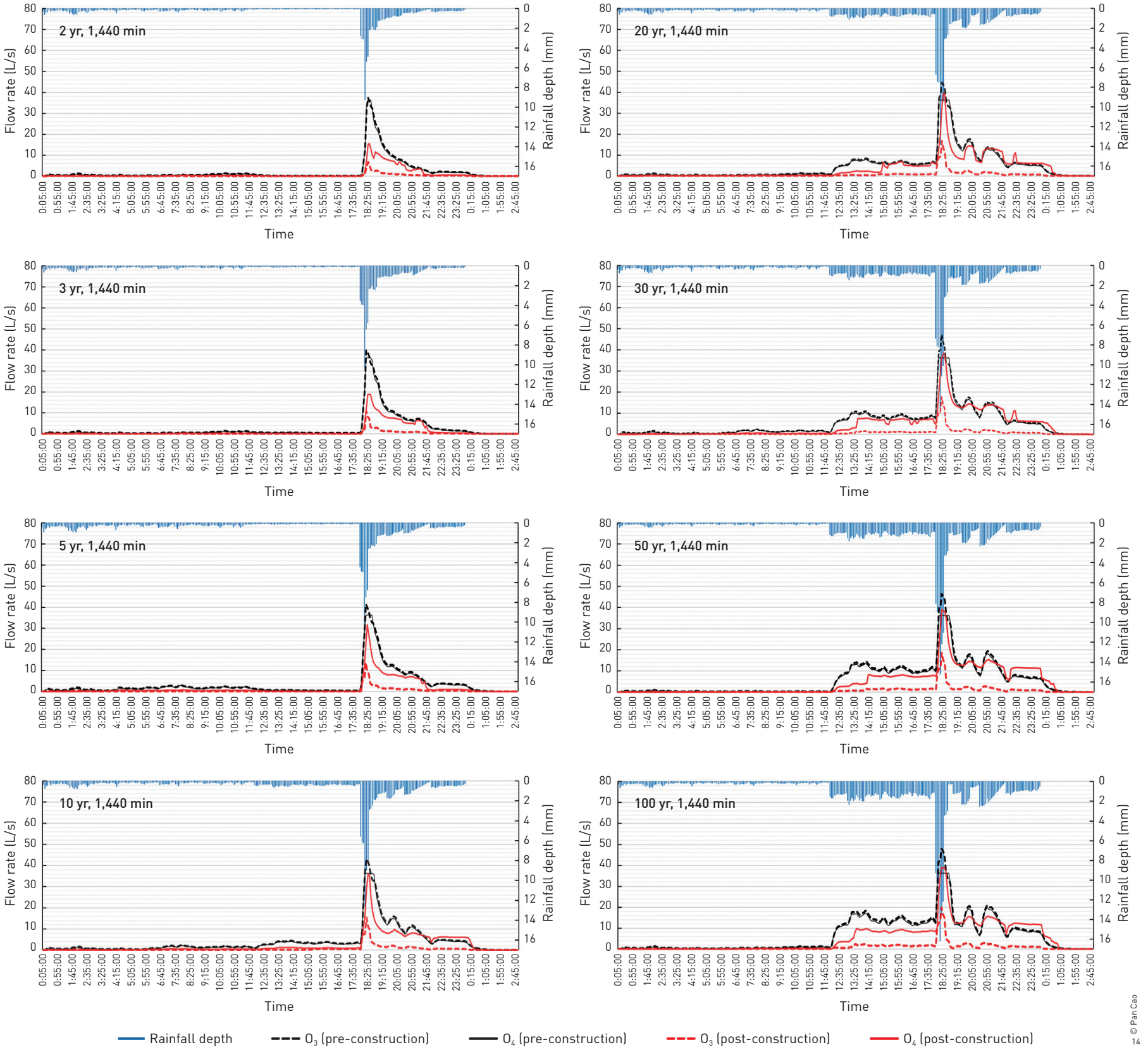


Fig. 14 Outflow hydrographs at outlets O_3 and O_4 before and after construction under long-duration rainfall events.

of the drainage system for intense rainfall with return periods of 20 yr and above.

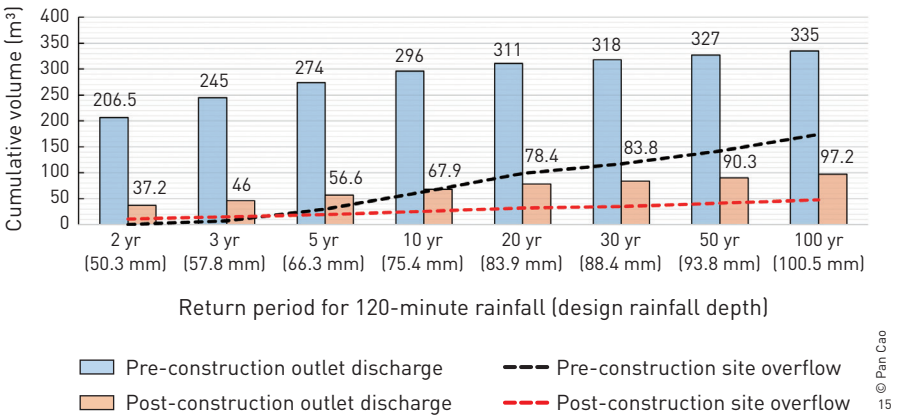
Based on site runoff characteristics, variations in total discharge at outlets O_3 and O_4 before and after construction reflect the stormwater management performance of the garden. Under short-duration rainfall for return periods of 2 yr, 3 yr, 5 yr, 10 yr,

20 yr, 30 yr, 50 yr, and 100 yr, the garden detains runoff volumes ranging from 169.3 m^3 to 237.8 m^3, with outflow reduction rates of 81.99%, 81.22%, 79.34%, 77.06%, 74.79%, 73.65%, 72.39%, and 70.99%, respectively. Overflow volumes at each return period are generally much lower than those under pre-construction conditions, leading to effective control of overflow (Fig. 15). For long-duration rainfall, although the total detained runoff increases to 292.4 m^3–705.1 m^3, the outflow reduction capacity generally decreases with rising return periods, with corresponding rates of 70.29%, 68.10%, 67.90%, 62.43%, 55.34%, 51.98%, 51.46%, and 53.87%. In particular, when the return period is no less than 30 yr, site overflow exceeds pre-construction values. This points to saturation in the garden's pluvial management capacity: its detention performance nears the practical upper bound, and the site's risk of on-site overflow becomes apparent (Fig. 16).

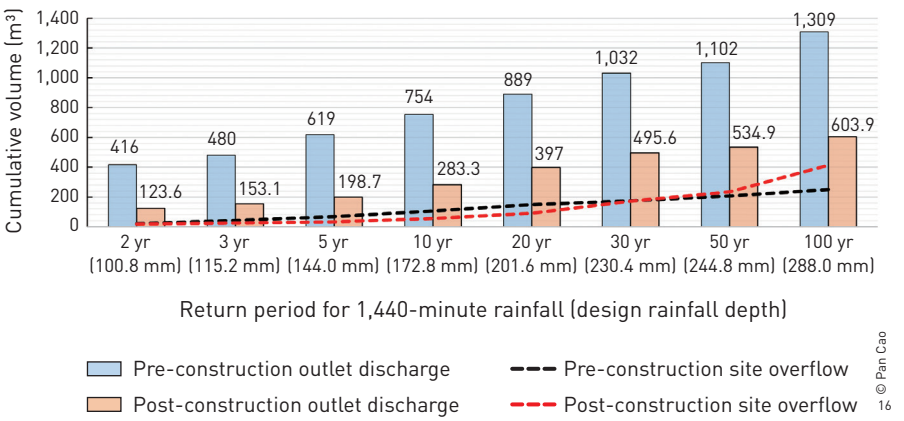
5 Discussion

Functional integration of site space constitutes the key to dual-use pluvial resilience design, and its long-term viability hinges upon cultivating a site-specific social network with active multi-stakeholder involvement. The Practice-Base Garden gains vitality through functional sharing and spatial openness: besides its primary role for teaching and practical training, it serves as a venue for showcasing the college's teaching approach and hosting exchanges. Its fully open layout breaks down barriers to interaction and creates a pleasant recreational space for nearby residents. Residents have also begun to clean the garden voluntarily. As a scarce outdoor public space within the older campus, it attracts students from other departments for informal gatherings (Fig. 17). Ongoing long-term research projects on site cultivate autonomy and agency among participants, supporting prompt identification of small changes in site conditions. Relevant cases include a 15-day power outage of the mini weather station during the Spring Festival and gravel-plaza ponding triggered by discharge from the Harbour and Navigation Center. Teaching, research, assembly, recreation, and fitness bring diverse stakeholders together. Rather than a network governed by one primary actor, a stable multi-stakeholder network for garden stewardship has developed through shared interests. This sustains the site's pluvial resilience over time.

Landscapes evolve over time under diverse rainfall regimes and form hydrologically adapted plant communities, an important consideration for dual-use pluvial resilience design. *Pycnonotus sinensis* build nests and lay eggs within the sun-loving garden; frogs croak around the bioretention pond, and *Elaphe taeniura* have been



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Fig. 15 Comparison of stormwater flow management performance in the Practice-Base Garden before and after construction under short-duration rainfall events.
Fig. 16 Comparison of stormwater flow management performance in the Practice-Base Garden before and after construction under long-duration rainfall events.
Fig. 17 Spontaneous use of the Practice-Base Garden as a multifunctional space.

recorded in this zone. The turfgrass *Zoysia japonica* 'Lanyin No. 3' planted on the gentle slope exhibits stratified growth aligned with contour lines, without regular mowing (Fig. 18). Dense vegetation develops at higher elevations, forming a distinct wetting boundary



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Fig. 18 Landscape of the grassy slope shaped by continuous stormwater retention and detention.

along the depth gradient. Robust plant growth occurs within this transitional zone, where *Artemisia lavandulifolia* emerges. Vegetation becomes sparse in low-lying areas, where *Kummerowia striata* appears, absent elsewhere on site.

6 Conclusions and Limitations

6.1 Conclusions

The Practice-Base Garden delivers notable stormwater management performance under short-duration rainfall events, with outlet flow reduction rates ranging from 70.99% to 81.99%. For long-duration rainfall, the reduction rate generally declines as return periods rise, falling between 51.46% and 70.29%. Using the total site overflow volume as the basis for comparison, the renovation increases the garden's capacity to manage rainfall events from a 2-year to a 30-year return period. Even without municipal network upgrades or underground storage modules, the stormwater management capacity of such multifunctional existing urban spaces can be substantially improved, enabling stormwater management at the source across different rainfall magnitudes.

The green space ratio within the design area was 81.4% pre-construction and 47.8% post-construction. Compared with the green space ratio, developing the site's retention and detention space serves as fundamentality for dual-use pluvial resilience, and site grading is critical to realizing this goal. For built settings with permeable green spaces, the core design criteria are inflow acceptance, complete infiltration, and safe drainage. Refined grading guides surface runoff into designated storage zones to accept inflow. The depression depth of bioretention zones is set from measured soil infiltration data to ensure runoff fully infiltrates within the time interval used for the rainfall frequency analysis to achieve complete infiltration. Safe drainage relies on unblocked emergency overflow paths for runoff beyond storage limits.

Sustained effectiveness of dual-use pluvial resilience hinges heavily on long-term stewardship and reliable facility operation. Sustainability is supported by multi-stakeholder networks formed through spatial openness and functional sharing. Reliability demands that facilities follow hydraulic principles during temporary storage and emergency overflow. The automatic delayed outflow design, which functions without manual intervention or external equipment, proves effective.

6.2 Limitations

No flowmeter was fitted at the Practice-Base Garden's catchment outlet during the preliminary phase. Subsequent upgrades to equipment in adjacent laboratory buildings triggered repeated revisions to the terminal overflow facilities, leaving no field flow records for real rainfall events. The SWMM model was calibrated primarily using the observed timing of surface runoff onset and recession, with carefully assigned parameters. Even so, the calibration method imposes inherent constraints on the accuracy of simulated outputs in some respects.

Safe and smooth overflow beyond site capacity depends on local conditions and backwater buildup in drainage networks under high external water levels. Located on the highest ground of the campus, the Practice-Base Garden receives no runoff from the other upstream areas. Its pluvial resilience design and analysis center on plot-scale hydrological characteristics, limiting comprehensive evaluation of systemic benefits. Future research should expand to basin scales to quantify allocation and coordination across source, conveyance and terminal stages.

The case campus has relatively unified land tenure and a subtropical monsoon climate. The transferability of the proposed pluvial resilience design framework awaits verification via more applications across diverse existing urban spaces and rainfall regimes.

ELECTRONIC SUPPLEMENTARY MATERIAL

Supplementary material is available in the online version of this article at https://doi.org/10.15302/J-LAF-2026-0052.

Competing interests | The authors declare that they have no competing interests.

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“平急两用”的校园雨洪韧性设计研究与实践

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摘要

极端天气与气候事件已成为人类社会可持续发展的重大挑战，中国城市的雨洪问题更是呈现出复杂性与系统性压力。本研究以一处校园内的低效存量空间改造为教学实践基地为研究对象，探讨建成环境中“平急两用”的雨洪韧性建设的一般途径：以空间开放与功能共享的原则架构场地功能分区，依托多方受益形成互惠格局，促成稳定向好的场地运维社会网络，为其雨洪管控效益的持续发挥提供保障；以“容积法”设计“平”时降雨情境下的常规消纳空间、以竖向统筹挖掘“急”时降雨情境下的临时滞蓄空间，两相叠加形成“平急两用”的雨洪调蓄空间；最后在汇流终端，模糊“平”“急”降雨情境的阈值边界，以无需人为干预的“自动延时出流”设计确保场地临时雨水调蓄与紧急溢流的可靠性、安全性。该基地自其建成运行以来已有41个月，经历不同等级降雨402场次，呈现出良好的雨洪管控实效。本研究中依托校园存量空间改造实践而构建的平急两用雨洪韧性建设模式，可为城市建成环境中的雨洪管控与功能复合利用提供实践范式。

关键词

平急两用；雨洪韧性；竖向设计；调蓄空间；SWMM；延时出流；海绵城市；开放空间

文章亮点

- 基地花园持续运行41个月，经历402场降雨，呈现出良好的雨洪管控成效
- 空间开放与功能共享有助于多方参与场地运维管理
- 自动延时出流设计无需人为干预，即可实现常规消纳、临时滞蓄与紧急溢流

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