# Beyond Theory: Ten-Year Evidence of Grey–Green Integration for 30-Year Flood Mitigation and Water Quality Restoration in Zhenjiang

## Au-delà de la théorie : dix ans de preuves d'une intégration gris-vert-bleu pour l'atténuation des inondations trentennales et la restauration de la qualité de l'eau à Zhenjiang (Chine)

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## RÉSUMÉ

Le projet pilote national « Ville-éponge » de Zhenjiang (2015–2025) constitue l'un des rares exemples au monde d'un système intégré vert-bleu-gris de gestion résiliente des eaux pluviales déployé à l'échelle d'un bassin versant urbain dense de 29,28 km². L'approche systémique mise en œuvre permet de maîtriser les pluies de période de retour 30 ans (256 mm/24 h), a totalement éliminé les inondations chroniques sur les 48 points noirs historiques et a restauré la qualité des eaux réceptrices jusqu'au standard chinois de classe III. La stratégie combine des principes de Développement à Faible Impact (LID) en source — visant à rapprocher l'hydrologie des sites aménagés de leur état pré-urbain — avec des ouvrages bleus de fin de parcours (zones humides à haute performance et parcs à double usage) qui assurent un stockage temporaire significatif des volumes excédant la capacité de dimensionnement 30 ans. L'épine dorsale grise est constituée d'un tunnel profond de 6,2 km et de 4 m de diamètre, enterré jusqu'à 34 m et traversant de manière unique le fleuve Yangtze, afin de collecter les ruissellements amont, des quartiers historiques et les débordements d'égouts unitaires (CSO) pour les diriger vers des bassins d'oxydation écologiques terminaux situés sur une île du fleuve. Dix années de suivi continu (40 stations automatisées) confirment des performances exceptionnelles en conditions réelles : aucun engorgement dans les 48 anciens points noirs sur des centaines d'épisodes pluvieux, rétention sur site >99 %, contrôle annuel du ruissellement ≥76 %. Le système a notamment résisté sans aucun dégât à l'ouragan In-Fa 2021 (312 mm en 72 h, période de retour >50 ans). Zhenjiang offre ainsi un modèle rigoureusement validé, directement transférable, d'infrastructure hybride pour les villes denses confrontées à l'intensification des risques pluviaux liés au changement climatique.

## ABSTRACT

The Zhenjiang Sponge City pilot (2015–2025) demonstrates a fully integrated green-blue-grey system for climate-resilient urban water management in a dense, 29 km² urban watershed. The project's systemic approach successfully manages 30-year return period storms (e.g., 256 mm/24 h), has effectively eliminated chronic waterlogging at all 48 historical hotspots, and enhances water quality to China's Class III standard. The core strategy combines Low Impact Development (LID) principles (restoring the developed sites' hydrology to pre-development conditions as close as possible) with end-of-pipe blue treatment facilities that are integral to Sponge City construction. These facilities, including the innovative high-performance wetlands and dual-use community parks, provide significant temporary storage for runoff exceeding the 30-year design. The critical "grey" backbone is a 6.2 km, 4-meter diameter deep tunnel, which is buried up to 34 meters and uniquely crosses the Yangtze River to convey upstream and heritage areas' runoff and Combined Sewer Overflows (CSOs) to terminal ecological oxidation ponds in an island in the Yangtze River. Ten years of monitoring and observations confirm exceptional real-world performance: retrofitted districts experienced no waterlogging incidents at any of the 48 former chronic hotspots across hundreds of storms with >99% onsite rainfall retention recorded. The system captures ≥76% of annual runoff and has proven to be a scalable, effective model for hybrid infrastructure in high-density cities worldwide.

**Keywords:** Urban Flood Mitigation, 30-Year Storm, Green-Blue-Grey Infrastructure, Sponge City, Zhenjiang, Water Quality, Climate Resilience.

## 1. INTRODUCTION

Rapid urbanization in China has dramatically increased impervious surfaces, intensifying pluvial flooding and diffuse pollution in many older cities. Zhenjiang, a historic city on the lower Yangtze River, faced not only recurrent summer waterlogging but also severe degradation of urban water bodies. Historical records documented 48 chronic flooding hotspots within the pilot area, with vulnerable, low-income communities being particularly troubled. These areas, situated at the lowest point of the drainage basin, suffered catastrophic annual waterlogging because they relied on a legacy drainage system designed only for a 1-year storm event. This hydraulic failure was compounded by widespread infrastructure deficiencies, including continuous sewer surcharge posing public health risks, illicit connections, and a profound lack of communal green and recreational space. These systemic failures accelerated community decline, driving out younger generations and leaving behind a population predominantly composed of the elderly and children.

In 2015, Zhenjiang was selected as a prestigious first-batch national Sponge City pilot with an ambitious, multi-objective mandate: to eliminate waterlogging under a 30-year return-period storm (256 mm/24 h), restore receiving-water quality to the national Class III standard, and capture a minimum of 75% of annual runoff.

This paper presents a 10-year retro-study and validation of the fully integrated green–blue–grey system implemented across the 29 km² core pilot area of the Jinshan Lake Watershed. The solution strategically combines distributed LID practices (bioretention, permeable pavements) for effective source control, end-of-pipe blue treatment facilities (innovative high-performance wetlands, dual-use community parks) for large-scale temporary storage for extreme rainfalls exceeding 30-years, and a critical grey backbone—a 6.2 km deep tunnel that uniquely crosses the Yangtze River—to intercept Combined Sewer Overflows (CSOs). Drawing on ten years (2015–2025) of monitored performance data, the study validates how this pioneering hybrid approach delivered full flood elimination and durable water-quality benefits, offering a highly replicable model for high-density cities worldwide.

## 2. METHODS

### 2.1 Study Area and Baseline Conditions

The Zhenjiang Sponge City pilot covers a 29 km² core urban watershed centered on Jinshan Lake characterized by high imperviousness (65–75%) and legacy drainage systems designed for only 1-year return period events. Baseline assessments (2007–2014) identified key challenges: 48 recurrent flooding hotspots with annual waterlogging in low-lying communities; combined sewer overflows (CSOs) causing black-odorous water in 2 rivers (among 5 inferior Class V waterbodies); and non-point source pollution from various land uses. Historical records showed rainfall-runoff patterns influenced by the Yangtze River confluence, with TMDL (Total Maximum Daily Load) analysis revealing annual pollutant loads into one lake and three rivers (e.g., COD 8148 t/a, $NH_3$-N 81 t/a, TP 28 t/a) exceeding capacity by 30–85%. The area was divided into 11 sub-basins for targeted evaluation, with baseline annual runoff control rates ranging from 38.7% to 57.1%.

### 2.2 System Design Framework

#### *2.2.1 Green Infrastructure (GI) for Source Control*

The first layer of the system focused on decentralized source control to manage the "first flush" and delay peak flow at the site-scale. This involved widespread retrofit and application of Low Impact Development (LID) practices throughout neighborhoods, roads, and open spaces:

- **Measures:** Implementation of bioretention cells, permeable pavements (using interlocking pavers to ensure long-term durability), and rain gardens.
- **Hydraulic Function:** These measures work to infiltrate, filter, and temporarily store rainfall, ensuring that over 99% of annual runoff from specific sub-catchments is detained or treated onsite.

#### *2.2.2 Blue Infrastructure for Regional Storage and Treatment*

The blue components are end-of-pipe treatment facilities integral to the Sponge City construction, providing essential capacity for flows exceeding the standard 30-year drainage system capacity.

- **Detention:** Implementation of a high-performance subsurface Wetland capturing 76 ha runoff in Mengjiawan Lake and 12 dual-purpose sponge city parks for ~450,000 m³ flood storage retaining upland water in upland areas to reduce downstream burden. These facilities temporarily hold extreme runoff volumes for flood peak attenuation.

- **Treatment:** Wetlands and parks are also key treatment stages, employing ecological processes to reduce pollutants (TSS, COD, NH3-N, TP) and improve water quality before eventual discharge.

#### *2.2.3 Critical Grey Infrastructure for Optimized Conveyance*

The grey system was simultaneously upgraded and integrated with green and blue components to optimize flow and reduce combined sewer overflow (CSO).

- **Deep Tunnel Construction:** A critical grey backbone was constructed: a 6.2 km long, 4-meter diameter deep tunnel (buried up to 34 m). This tunnel's unique design includes crossing the Yangtze River to intercept runoff for heritage areas and CSOs from the core urban area.

- **Pollution Conveyance:** The tunnel's primary function is to efficiently convey intercepted runoffs and CSOs to terminal ecological oxidation ponds for centralized treatment, thereby eliminating chronic water quality degradation caused by sewer surcharge in the old drainage network.

#### *2.2.4 Hydrologic, Hydraulic, and Water-Quality Modeling*

A coupled modeling framework (HSPF for watershed hydrology, SWMM for urban drainage, HEC-RAS for river hydraulics, and EFDC for lake water quality) simulated the 139 km² basin, 660 km pipe network, and 65 km rivers/6.5 km² lakes. Models were calibrated with local data on event-mean concentrations and 1980–2014 rainfall records, targeting on 30-years storm event for flood mitigation and water-quality event for 75–80% annual runoff control. Pollutant load distributions and reductions were mapped per outfall. Scenarios evaluated source-process-system overlays, confirming 93% inundation reduction in 47 retrofitting communities.

#### *2.2.5 Monitoring and Validation (10-Year Retro-Study)*

The system's performance was validated through a **10-year retrospective study (2015–2025)** using real-world observations and monitoring data:

- **Hydrological Monitoring:** Continuous data on rainfall intensity, runoff volume, and peak flow attenuation were collected to verify the system's capacity to handle rainfall depths associated with the 30-year storm and confirm the elimination of waterlogging.

- **Water Quality Assessment:** Regular sampling and analysis of receiving water bodies were conducted to track pollutant reductions (TSS, COD, NH3-N, TP) and verify the achievement of the Class III water quality standard.

- **Performance Metrics:** The study focused on verifiable metrics, including the number of flood events mitigated, percentage of annual runoff captured, and pre- and post-retrofit pollutant loads.

## 3. RESULT AND DISCUSSION

The long-term performance data, gathered over a 10-year monitoring period (2015–2025), confirm that the integrated Green-Blue-Grey (GBG) system effectively achieved the ambitious mandates set for the Zhenjiang Sponge City pilot.

### 3.1 Longitudinal Hydrological Efficacy and Flood Mitigation

The verifiable long-term resilience of the integrated green-blue-grey system represents the most significant finding of this decade-long study. Prior to retrofitting, intense rainfall events routinely caused severe waterlogging: for example, the 27 May 2013 storm (85 mm in 24 h) produced ponding depths of 200–500 mm across low-lying neighborhoods. In contrast, during the entire 10-year post-implementation monitoring period (2015–2025), all 48 previously chronic flood hotspots recorded no waterlogging incidents under recurrent heavy rainfall (Figure 1).

**Source-Control Performance:** High-frequency monitoring at 40 automated stations confirmed the exceptional efficacy of the distributed Green Infrastructure (GI) components. On-site rainfall retention exceeded 99 % during multiple high-intensity events (>50 mm/h), with bioretention cells, permeable pavements, and Active Bioretention Systems effectively attenuating peak flows at the source and preventing surface runoff from entering the grey conveyance system in all but the most extreme tails of recorded storms.

This extraordinary performance was conclusively demonstrated during Typhoon In-Fa (25-28 July 2021), the most severe event since project completion. In-Fa delivered 312 mm of cumulative rainfall over 72 h in central Zhenjiang (exceeding a 50-year return period at several gauges) with a peak 6-hour intensity of 152 mm - far surpassing the original 30-year design storm of 256 mm/24 h. Despite these extreme conditions, no surface ponding lasting longer than 15 minutes occurred in any retrofitted district, and all 36 officially designated historical inundation points remained completely dry including the previously most vulnerable Jiangbin New Village - one of China's most notorious pre-2015 flooding locations-experienced experienced no lasting surface water accumulation throughout the typhoon (Figure 2), providing definitive field validation that the hybrid system substantially exceeds the targeted 30-year resilience standard under real-world extreme conditions.

## 3.2 Water Quality Improvement and Pollutant Reduction

The integrated GBG system produced rapid and sustained restoration of receiving water bodies. Two officially designated black-odorous watercourses (Yiye River and Hongqiao Port River) were eliminated within 18 months of completion, with no recurrence observed over the subsequent years (2019-2025). Continuous monitoring at 12 in-lake and 28 riverine stations confirmed that Jinshan Lake and the three main urban rivers (Guyun River, Yunliang River, and Hongqiao Port) consistently achieved or exceeded China's Surface Water Quality Standard Class III (equivalent to moderate ecological status under the EU Water Framework Directive). The overall compliance rate across all monitored water bodies reached 92.3%.

Quantified annual pollutant load reductions to receiving waters, calculated from flow-proportional sampling at 60 major outfalls and terminal treatment facilities, were:

- COD: 77% reduction (~6,300 t/a removed)
- $NH_3$-N: 62% reduction (~50 t/a removed)
- Total Phosphorus: 82% reduction (~23 t/a removed)
- Total Suspended Solids: >85% reduction during both wet-weather and dry-weather flows

These reductions were sustained even during extreme events, including Typhoon In-Fa (2021), demonstrating that the hybrid infrastructure maintained high treatment efficiency under peak hydraulic loading.

### 3.3 System Resilience, Scalability, and Global Relevance

Distributed green stormwater infrastructure (GSI) and blue infrastructures captured and treated an average of 76.06% of annual runoff volume across the 29 km² pilot area, with onsite retention exceeding 99% for most individual rainfall events in more than 40 communities retrofitted, including bursts up to 76.2 mm/h. The entire pilot area has met or exceeded all 16 national Sponge City performance indicators for over ten years, with no waterlogging incidents recorded at 48 historical hot spots including during Typhoon In-Fa (312 mm/72 h, >50-year return period).

The Zhenjiang case provides one of the world's most rigorously documented examples of full-scale, decade-long success of hybrid green-blue-grey infrastructure in a high-density, legacy urban environment. Its technical framework, institutional mechanisms, and community co-governance model have been officially recognized by the Chinese Ministry of Housing and Urban-Rural Development as the transferable "Zhenjiang Sponge City Model," offering a directly replicable blueprint for cities worldwide facing intensifying pluvial flooding, combined-sewer overflows, and urban water-quality degradation under climate change.

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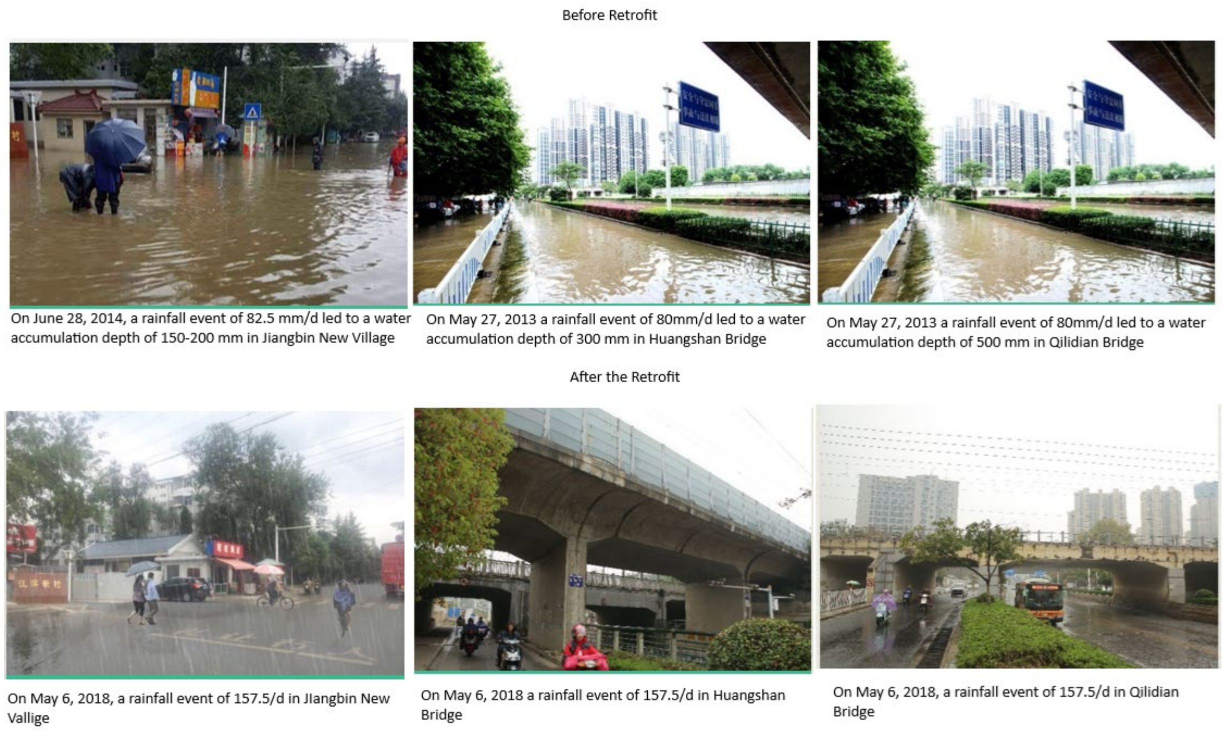



Figure 1. Comparisons of the Sponge City retrofit before and after heavy storm events

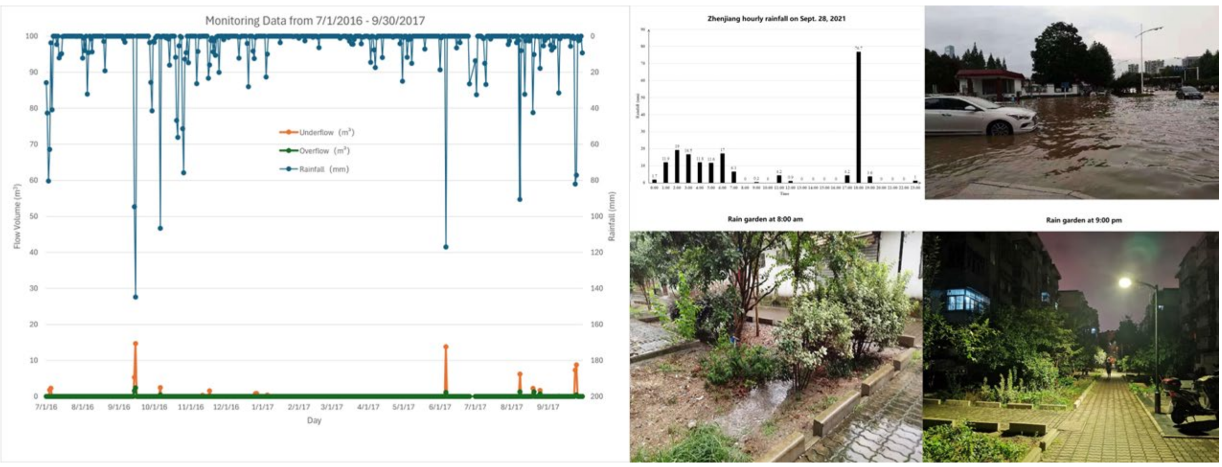
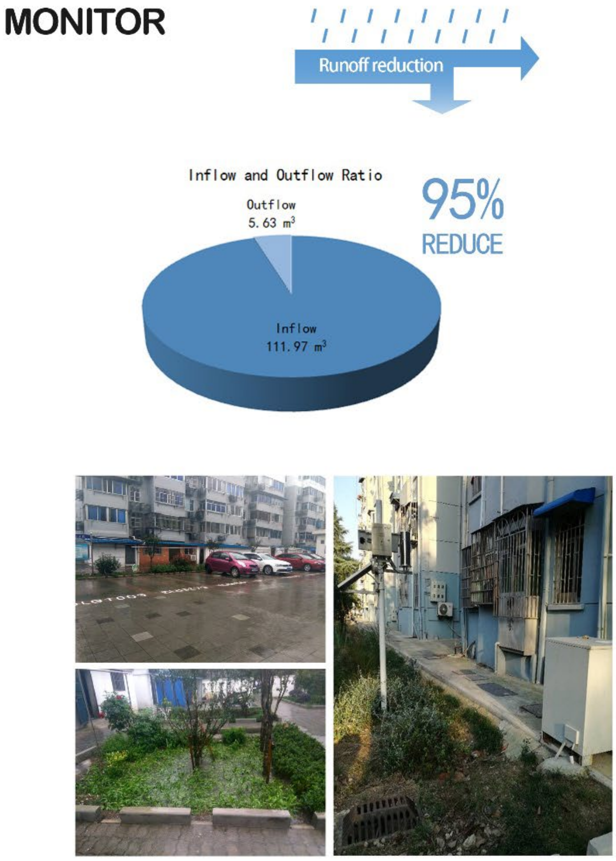
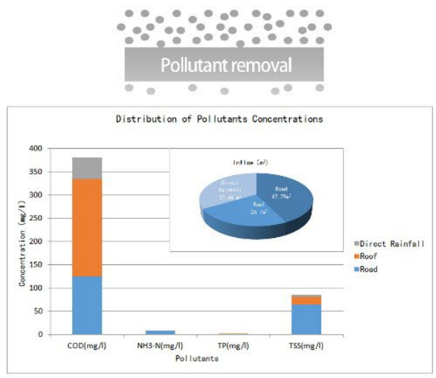



Figure 2. All flood-prone communities retrofitted in 2015 experienced NO waterlogging in the subsequent 10 years.>99% of rainfall was detained onsite




| Land Use Type | COD(mg/l) | $NH_3$-N(mg/l) | TP(mg/l) | TSS(mg/l) | Inflow ($m^2$) |
|---|---|---|---|---|---|
| Road | 125.09 | 7.57 | 0.21 | 64.73 | 47.79 |
| Roof | 209.45 | 0.26 | 0.07 | 16.36 | 26.7 |
| Direct Rainfall | 46.27 | 0.25 | 0 | 4.73 | 37.48 |
| Concentration | 118.82 | 3.37 | 0.11 | 33.11 | 111.97 |

| | | Loading (kg) | Removal (%) |
|---|---|---|---|
| Concentration(mg/l) | 33.11 | | |
| Inflow ($m^3$) | 111.97 | 3.7073 | 0.9827 |
| Outflow Concentration(mg/l) | 11.36 | | |
| Outflow ($m^2$) | 5.63 | 0.064 | |

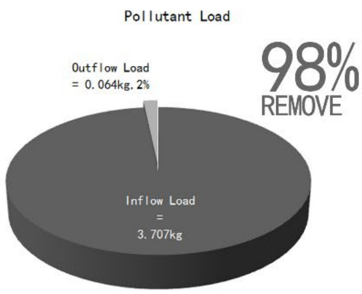



Figure 3. Pollution load reduction in communities