

Nature-Based Solutions for Disaster Risk Reduction: Sponge Cities Increase Resilience, Reduce Risks, and Lower the Costs of Floods

Joel Thomas 

School of Education and Human Development, University of Miami, Coral Gables, FL, USA
Email: joelthomasteacher@gmail.com

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Abstract

Recent catastrophic flooding events across the globe have starkly highlighted the vulnerability of urban centers designed around 20th-century climate norms. As hydro-meteorological hazards intensify globally, China's large-scale investment in nature-based urban design offers a critical case study in cost-saving long-term resilience. This article examines the value proposition of the Sponge City concept, a paradigm shift in urban water management pioneered by Dr. Kongjian Yu and implemented across China, as a strategic response to increasing climate volatility. We evaluate and compare the economic, social, and environmental costs and savings of the integrated Green Infrastructure-Sponge City approach vs. the conventional Grey Infrastructure approach to sustainable urban adaptation, providing a framework for decision-making.

Keywords

Climate Adaptation, Disaster Risk Reduction, Flood, Green Infrastructure, Resilience, Sponge City, Stormwater, Sustainability, Urban Planning

1. Introduction: From Grey to Green-Grey Infrastructure

In the heart of our modern metropolises worldwide, a crisis has been threatening to submerge our homes and lives into chaos. 1.81 billion people are exposed to floods worldwide and floods now cost an average of USD 388.4 billion dollars annually [1] [2]. Most flood-related deaths and economic losses are recorded in Asia. In China in 2025, intense rainfall triggered flooding in Beijing, Guizhou, and Gansu, leaving over 80 people dead, forcing 80,000 people to evacuate, and triggering a partial collapse of Houzhé Grand Bridge [3] [4]. In 2024, China's Yangtze

River flooded for the first time, and six Chinese provinces experienced major flooding, causing an estimated 5.05 billion yuan (USD 695 million dollars) in damage to infrastructure, as well as forcing 110,000 citizens of Guangdong to relocate due to floods inundating homes [5]. In July 2023, unprecedented rainfall due to typhoons Doksuri and Khanun in several provinces in China triggered devastating floods that overwhelmed infrastructure [6]. Mere weeks later, similar scenes unfolded in Europe, North America, and North Africa, where Storm Daniel caused catastrophic dam failures in Libya [7]. These events underscore a critical juncture in urban planning, as traditional grey infrastructure, which includes concrete sewers, channels, and levees designed for historical precipitation data, is becoming increasingly inadequate against climate change-amplified superstorms.

In response to this mounting crisis of increasingly severe weather events, increased rainfall, and rapidly increasing urbanization, a nature-based solution, dubbed the “Sponge City,” has moved from theoretical concept to large-scale national policy in China. Spearheaded by landscape architect and professor Dr. Kongjian Yu, this approach represents a fundamental reimagining of the urban relationship with water, prioritizing absorption and reuse over rapid expulsion.

The Sponge City Initiative (SCI), formally launched by the Chinese government in 2015, aims to retrofit existing cities and guide new development to act like sponges [8]. The main objective is for 80% of urban areas to absorb and reuse at least 70% of stormwater runoff by 2030.

Dr. Yu, founder of the architecture firm Turenscape and a professor at Peking University, developed the concept based on ancient Chinese agricultural water management and modern ecological principles [9]. The Sponge City is not merely a set of technologies; it is a philosophical shift in how we perceive and manage water in the urban environment. Instead of seeing stormwater as a waste product to be disposed of, it is now valued as a precious resource to be captured, cleansed, and reused. His work argues that grey infrastructure creates a fragile, centralized system prone to catastrophic failure (Figure 1). In contrast, sponge cities employ decentralized green infrastructure (GI), which is made of natural resources (Table 1).

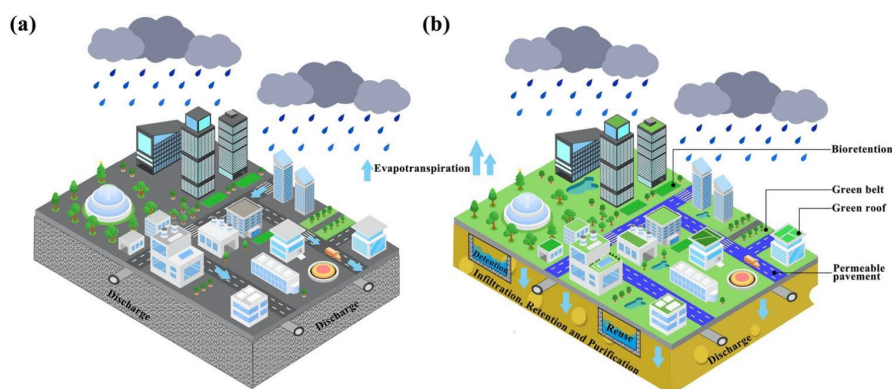


Figure 1. Hydrological processes of grey infrastructure (a) vs. green infrastructure (b).

Table 1. Grey vs. green infrastructure comparison.

	Grey infrastructure	Sponge City - green infrastructure
Primary purpose	The conventional approach is designed to transport and control water. It gets rainwater away from the city quickly through pipes and canals.	This integrated approach is designed to absorb and reuse water. It allows rainwater to infiltrate, be stored, evaporate, and be reused within the city.
Primary components	Concrete pipes, culverts, tunnels, detention tanks, concrete-lined channels, and wastewater treatment plants.	Permeable pavements, constructed wetlands, bioswales, and sunken parks
Capital cost	Very high due to large-scale concentrated construction.	High but variable due to distributed systems and adaptability to land constraints.
Lifespan	50 - 100 years	It can be self-renewing if ecologically managed.
Resilience	Brittleness occurs because infrastructure fails beyond its design capacity.	Adaptive because infrastructure improves with maturity and diversity.
Co = benefits	Minimal to none	Extensive (economic, environmental, social).
Implementation & governance	Centralized implementation with top-down governance.	Distributed implementation requires community engagement.

Green infrastructure found in Sponge Cities includes but is not limited to—permeable pavements, constructed wetlands, bioswales, and sunken parks—to create a resilient, distributed network that manages water at its source [10].

The Sponge City is not a single project; it is an ecological system built for water resilience and created for human beings to live in harmony with nature (Figure 2).

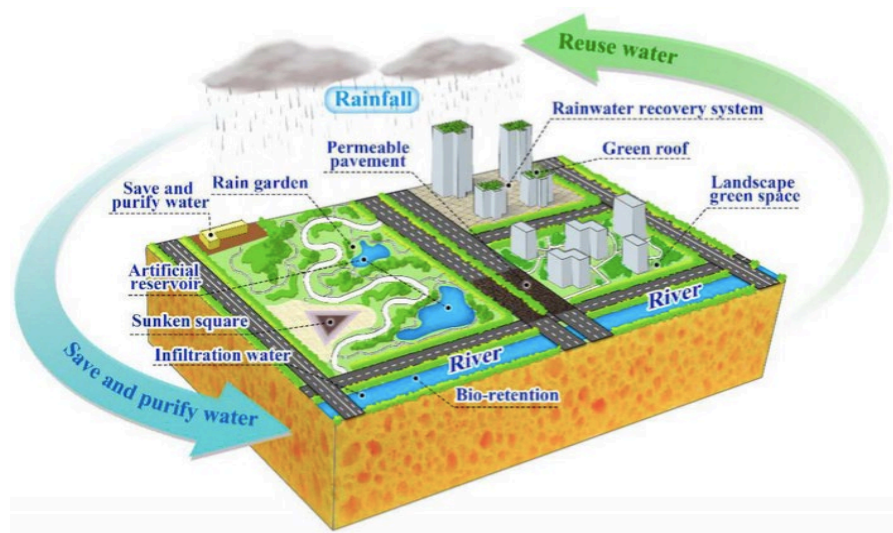


Figure 2. Anatomy of a Sponge City.

A Sponge City employs a diverse toolkit of techniques designed to manage wa-

ter and its source. These techniques can be categorized by their primary function in the urban water cycle: capturing, slowing, cleaning, absorbing, and storing.

1.1. Capturing and Slowing Runoff

The primary objective is to prevent rainwater from becoming surface runoff or to slow its flow dramatically.

1) **Permeable Pavements:** These include porous asphalt, pervious concrete, and interlocking permeable pavers. They allow water to infiltrate through the surface into an underlying stone reservoir base, where it is temporarily stored before slowly percolating into the subsoil. They are ideal for parking lots, sidewalks, and low-traffic roads, significantly reducing peak runoff volume [11].

2) **Green Roofs and Rooftop Gardens:** By covering rooftops with a waterproof membrane, drainage layer, growing medium, and vegetation, green roofs absorb rainfall and reduce the volume and rate of runoff. Green roofs can provide insulation, mitigate the urban heat island effect, and create habitats for biodiversity [12].

3) **Rain Gardens and Bioswales:** These are shallow, landscaped depressions designed to capture and treat stormwater runoff from adjacent impervious areas like streets and roofs. Filled with engineered soil and planted with native, water-tolerant vegetation, they filter pollutants through physical filtration and biological uptake. Bioswales are typically linear, acting as vegetated channels that convey water while facilitating infiltration [13].

1.2. Cleaning and Filtering Water

Urban runoff is polluted with heavy metals, oils, and sediments. Sponge City features act as natural, decentralized water treatment plants.

1) **Constructed Wetlands:** These are engineered ecosystems designed to mimic the water purification functions of natural wetlands. They are highly effective at treating stormwater or even wastewater through a complex interaction of soil, plants, and microbial communities which can remove sediments, nitrogen, phosphorus, and pathogens [14].

2) **Vegetated Filter Strips:** These are gently sloping areas of dense, permanent vegetation situated between a pollution source (e.g., a roadway or agricultural field) and a receiving waterbody. They function by slowing runoff velocity, allowing suspended particles and associated pollutants to settle out and be filtered by the plant root systems [15].

1.3. Absorbing and Storing Water

The ultimate goal is to recharge groundwater aquifers or to save water for non-potable uses.

1) **Infiltration Trenches and Basins:** These are excavated trenches or basins filled with stone or gravel that provide temporary subsurface storage of stormwater runoff. The stored water gradually infiltrates into the surrounding soil, directly re-

plenishing groundwater supplies [16].

2) Rainwater Harvesting: A simple yet highly effective technique involving the collection and storage of runoff from roofs into tanks or cisterns. The harvested water can be used for landscape irrigation, toilets, and other non-potable uses, which significantly reduces demand on municipal water supplies [17].

3) Multifunctional Retention and Detention Spaces: Modern Sponge City design promotes spaces that serve multi-faceted purposes. A classic example is a park designed with a sunken topography that functions as a playing field or amphitheater in dry weather but becomes a temporary retention pond during a heavy rain event, safely storing excess water and slowly releasing it after the storm [18].

2. Literature Review

The Sponge City concept, although innovative, is not an isolated invention but a synthesis and scaling-up of pre-existing international concepts. The philosophical and technical roots of Sponge Cities are an evolution of the following precursors:

1) Low Impact Development (LID) in the United States emphasizes managing stormwater at the source using decentralized micro-scale controls [19].

2) Sustainable Drainage Systems (SuDS) in the UK promote a “management train” approach with a focus on water quality, quantity, and amenity [20].

3) Water Sensitive Urban Design (WSUD) in Australia integrates urban water cycle management into urban design, including stormwater, groundwater, and wastewater [21].

4) The Chinese Sponge City initiative distinguishes itself through its scale and top-down mandate. It aims for cities to absorb, store, infiltrate, and purify up to 70% of stormwater runoff, with specific targets for annual runoff control (e.g., 70% - 80% volume capture) [22]. The core idea is to create a city that acts like a sponge—resilient and adaptive to environmental changes.

The SCI began with 16 pilot cities and has since expanded to over 30. Projects like the Qunli Stormwater Park in Harbin and the Yanweizhou Park in Jinhua, designed by Turenscape, serve as flagship examples [23]. These projects demonstrate multi-functionality: they are public amenities that also provide flood mitigation, water purification, and habitat restoration.

Early research indicates promising results. A study of Sponge City districts in Shanghai found a significant reduction in runoff volume and peak flow compared to traditional urban areas during standard rainfall events [24]. Furthermore, co-benefits include reduced urban heat island effect, improved air and water quality, and enhanced biodiversity [25].

However, the program’s efficacy against extreme events, precisely the ones it is meant to guard against, remains a subject of intense study. The 2021 Zhengzhou floods, which impacted a Sponge City pilot area, revealed limitations. While some reports indicated sponge city districts experienced less water accumulation and faster drainage, the system was overwhelmed by the historically unprecedented volume of rain [26]. This has led to a critical review of whether cities have created

enough sponge-like infrastructure and how sponge-like infrastructure can be integrated with grey infrastructure [27]. Further investigation is warranted to evaluate if cities have built enough sponge-like infrastructure to handle severe rainfall, especially cities that have borrowed the popular term “Sponge City” to secure funding from the central government and claim their city is a “sponge city.”

3. Discussion

3.1. Global Relevance, Challenges, and Benefits of Sponge Cities

The principles underlying the sponge city are not China-specific. Nature-based solutions (NBS) for urban water management are being explored from the Netherlands’ “*room for the river*” programs to the United States’ green infrastructure policies [21]. The IPCC’s Sixth Assessment Report explicitly recommends leveraging green infrastructure for climate adaptation, highlighting its cost-effectiveness and ancillary benefits [7].

The primary challenges for widespread adoption are fourfold:

1. *Financial Challenges:*

The cost of retrofitting existing dense urban areas is massive. Estimates suggest a cost of between 100 million and 1 billion RMB or \$14 - \$140 million USD per square kilometer [10]. This has led to heavy reliance on debt-financed local government investment vehicles, creating sustainability concerns.

2. *Retrofitting Complexity:*

Integrating GI into dense, existing urban fabric is logistically and financially demanding. Identifying suitable sites for infiltration in crowded cities with complex underground utilities is difficult. Furthermore, green infrastructure requires regular, knowledgeable maintenance (e.g., cleaning silt from bioswales, weeding rain gardens) to remain effective, a responsibility that is often overlooked or underfunded [28].

3. *Governance:*

Successful implementation requires unprecedented coordination across municipal departments (water, transport, parks) often working in silos. Traditional urban planning governance separates water, drainage, transportation, parks, and planning into different departments. The integrated nature of the Sponge City requires breaking down these silos, a process that is politically and culturally challenging [24].

4. *Performance Metrics:*

Long-term, standardized data on the performance of large-scale GI networks against extreme events are still being collected. There is a lack of long-term, standardized data to quantitatively assess the performance of Sponge City Projects at the watershed scale. This makes it difficult to optimize designs and justify continued investment [29].

The multifaceted dividends of the Sponge City model extend far beyond flood mitigation and water conservation, creating the following benefits.

5. *Environmental Benefits:*

1) *Enhanced Biodiversity*: Green corridors, parks, and wetlands create crucial habitats and stepping stones for urban wildlife, supporting pollinators and increasing ecological connectivity [30].

2) *Improved Air Quality and Microclimate*: Vegetation absorbs air pollutants (e.g., PM2.5, Nox), and through evapotranspiration, mitigates the urban heat island effect, making cities cooler and more comfortable [31].

3) *Carbon Sequestration*: Plants and soils in green infrastructure systems capture and store atmospheric carbon dioxide.

6. *Economic Benefits*:

1) *Reduced Flood Damage*: The primary economic benefit is the avoidance of billions of dollars in damages to property, infrastructure, and business interruptions from flooding.

2) *Cost-Effectiveness*: In many cases, a green-grey hybrid solution is more cost-effective over its lifecycle than a purely grey infrastructure solution [32].

3) *Increased Property Values*: Proximity to well-maintained green and blue spaces is correlated with higher property values and increased attractiveness for investment [33].

7. *Social and Health Benefits*:

1) *Improved Public Health*: Access to green spaces is linked to reduced stress, improved mental well-being, and encouragement of physical activity [34].

2) *Community Cohesion and Aesthetics*: Beautiful, accessible parks and water features become focal points for community interaction and recreation, enhancing social capital and overall quality of life.

3) *Educational Opportunities*: These visible systems serve as living laboratories, raising awareness about hydrology, ecology, and sustainability.

3.2. A Cost Comparative Analysis of Grey vs. Green Infrastructure

A comprehensive evaluation must transcend direct financial metrics. We analyze savings through the lens of four interconnected capitals:

1) *Economic Capital*: Direct costs, avoided damages, and operational efficiencies.

2) *Natural Capital*: Enhancement of Ecosystem Functions and Biodiversity.

3) *Social Capital*: Improvements in public health, equity, and community well-being.

4) *Adaptive Capital*: The capacity to learn, adjust, and cope with unforeseen shocks and stressors.

Capital Expenditure (CAPEX) is high for grey infrastructure, which requires large-scale, end-of-pipe solutions (e.g., deep tunnels). Costs are concentrated and escalate non-linearly and can be higher or lower depending on sectors and timelines. There is potential for significant savings by downsizing grey systems.

The groundbreaking case study for a Sponge City in Philadelphia, USA, projected \$9 billion in savings by using green infrastructure to meet *Clean Water Act* obligations instead of a grey-only tunnel system [35]. This demonstrates the po-

tential for Sponge Cities to avoid massive, singular capital outlays.

In terms of Operational and Maintenance Expenditure (OPEX) for Grey Infrastructure, lifecycle costs can be high and more energy-intensive. Maintenance requires consistent landscape management and pipe repairs.

Life-cycle cost analyses often show lower OPEX for nature-based solutions such as Sponge Cities [36]. The OECD (2021) notes that while maintenance is different, the energy savings and reduced mechanical complexity can lead to 15-40% lower lifetime costs.

In terms of avoided costs and risk transfer, nature-based solutions such as Sponge Cities avoid direct, insured flood damage. Reduced Combined Sewer Overflows (CSO), lower water treatment costs, mitigated urban heat island effects, and enhanced property values are co-benefits of Sponge Cities that translate into direct financial savings. A study of Copenhagen's cloudburst plan found green solutions provided a Benefit-Cost Ratio (BCR) of 1.4 - 2.0, primarily from flood damage avoidance [37].

Urban Heat Island Mitigation is negligible in Grey Infrastructure or even contributory because impervious surfaces absorb heat. Significant cooling via evapotranspiration and shading of Green Infrastructure embedded in Sponge Cities can generate further savings in the form of social capital. For example, reduced energy demand for air conditioning (5% - 10%) and lower public health costs during heatwaves are well-documented benefits of the ecosystem service of urban green spaces [38].

Air and water quality improvement can also be compared in grey versus green infrastructure. Grey infrastructure can exacerbate water pollution via CSOs. Green infrastructure can improve air and water quality through filtration, phytoremediation, and particulate matter deposition, resulting in monetizable health benefits from reduced respiratory and cardiovascular disease. Bratman *et al.* (2019) link urban nature exposure to measurable reductions in healthcare costs. Furthermore, sponge cities create recreational green spaces, reducing stress and promoting physical activity. Savings can be quantified and measured through reduced healthcare expenditures and increased productivity. Studies show access to green space is correlated with lower rates of depression and anxiety [34].

In terms of Natural Capital, Sponge Cities enhance urban biodiversity, providing corridors for species. Biodiversity underpins ecosystem resilience and provides intrinsic value, contributing to cultural services [39].

Finally, the paramount advantage of the Sponge City is its contribution to adaptive capacity.

Grey Infrastructure operates with a "cliff-edge" failure mode. It is designed for a specific capacity and can fail catastrophically when exceeded [40]. Its performance is static. Sponge Cities, in comparison, provide adaptive capacity because the system is distributed and provides functional diversity. If Sponge Cities exceed their water threshold, the system fails gracefully. The Sponge City's performance can improve as landscapes mature, and it offers benefits (e.g., recreation, cooling)

even during non-storm events. This capacity to manage uncertainty and learn from system performance constitutes a major, though often unquantified, saving [41].

4. Conclusion

The evidence demonstrates that the Sponge City paradigm offers a fundamentally different and more valuable savings proposition than grey infrastructure. The savings are not merely financial but are embedded in the enhancement of natural, social, and adaptive capital. While initial CAPEX may be comparable or context-dependent, the life-cycle savings from avoided costs, risk reduction, and a multitude of co-benefits present a compelling economic case for further investment in Sponge Cities. In an era of climate uncertainty, the resilience dividend of Sponge Cities, and their ability to adapt and provide continuous value, make them an indispensable strategy.

However, Sponge Cities are not a panacea. I argue that the optimal solution is a hybrid grey-green system, where the Sponge City measures act as the first line of defense, reducing the volume and peak flow directed to the essential, but downsized, grey infrastructure backbone [21]. This hybrid approach must take into account geological suitability (e.g., contaminated soils, high water tables), land constraints in dense urban cores, and novel maintenance regimes in order to maximize economic and resilience savings.

China's Sponge City Initiative is the world's most ambitious experiment in urban flood adaptation using nature-based solutions. While not a silver bullet for all flooding, it provides a crucial blueprint for building multi-functional resilience. The lessons learned—both its successes in managing common rainfall and its struggles with black-swan events—are invaluable for a global community of urban planners, hydrologists, and policymakers. As the climate continues to change and urban populations continue to grow rapidly, the vulnerabilities of traditional grey infrastructure will only become more pronounced. Sponge Cities offer a proactive and beautiful alternative. By learning to absorb, adapt, and reuse water, our cities can transform from vulnerable concrete jungles into thriving, sustainable ecosystems. Future urban water management must prioritize the integration of these principles to build cities that are not only safer but also more livable, sustainable, and economically robust. As climate uncertainty grows, the paradigm shift from fighting water to living in harmony with it, as championed by Dr. Yu, may well become the foundation for a Sponge Planet of 21st-century urban survival.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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