Citation (APA)
Naghibi, M., Weber, G., Vamvakousi, E., & Forgaci, C. (2026). Context-sensitive Sponge City strategies: A cross-case and multi-scalar analysis. *Cities*, *178*, Article 107320. https://doi.org/10.1016/j.cities.2026.107320

Cities 178 (2026) 107320

Contents lists available at ScienceDirect

Cities

journal homepage: www.elsevier.com/locate/cities

Context-sensitive Sponge City strategies: A cross-case and multi-scalar analysis

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ARTICLE INFO

Keywords:
Sponge Cities
Landscape typologies
Social dimensions
Design and society
Urban resilience
Climate adaptation

ABSTRACT

Sponge Cities are more than technical solutions to urban flooding–they are dynamic spaces where water, land, and society converge in adaptation and resilience. This study bridges theory and practice through a comparative, cross-case framework that analyzes Sponge City strategies across five Dutch lowland landscape types (coastal, riverine, peat, sandy, clay) and selected international contexts.

Emphasizing scale as a critical dimension, the study explores how blue, green, and blue-green strategies are shaped by ecological conditions and local practices. Beyond hydrological performance, it highlights the often-overlooked social dimension, including community participation, equity, and social resilience.

The research adopts a qualitative, interpretivist methodology, combining within-case and cross-case analysis. It unfolds in two phases: first, a global typology of 38 Sponge City strategies is developed, categorized as green, blue, or green-blue, and analyzed by spatial scale (site, neighborhood, city), sponge basin principles (protect, delay, store, release), and hydrological processes (infiltration, retention, storage, purification, utilization, drainage). The second phase offers an in-depth evaluation of eight Dutch projects across Amsterdam, Rotterdam, Almere, Purmerend, and The Hague, examining ecological, spatial, and social performance through thematic coding and structured comparison.

The findings highlight a gap between the coherence of Sponge City theory and its real-world application, particularly regarding social integration. Successful implementation depends on context-sensitive strategies that go beyond water management to include accessibility, inclusivity, and community engagement. This study contributes to a broader understanding of how human-centered, adaptive design can support climate resilience across diverse urban landscapes, grounding its analysis in a landscape-based Sponge City framework that links Sponge Basin principles (protect, delay, store, release) with lowland landscape typologies and cross-scalar design strategies.

1. Introduction

1.1. Evolving strategies for urban water resilience

Water management strategies differ across the world, shaped by climate, geography, and cultural traditions. While some nations have focused on engineered drainage and flood control, others have developed adaptive systems that integrate water into daily life and urban resilience (Nguyen et al., 2019; Zha et al., 2021; Zhao et al., 2019). France (1852) and the UK (1859) integrated drainage into urban planning (Lehmann, 2010), while Japan's Rainwater Retention and Infiltration Plan (1920) emphasized absorption over diversion. By the 1990s, Germany pursued zero increase in drainage, and Tokyo (1992) constructed one of the world's most advanced sewer systems (Zeng et al., 2023). The U.S. and Australia, since the 1970s, have pioneered low-impact development and in-situ flood storage, reframing stormwater as a resource rather than a liability. In the Southern Hemisphere, water sensitive urban design (WSUD) in Australia and New Zealand continues to integrate ecological principles with urban planning and urban form (du Toit, 2025; Khalaji et al., 2025). Bangladesh's floating gardens offer a nature-based model, sustaining communities through seasonal floods. The Persian Qanat system, an early hydrological innovation, sustained

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https://doi.org/10.1016/j.cities.2026.107320
Received 12 September 2025; Received in revised form 24 February 2026; Accepted 29 June 2026

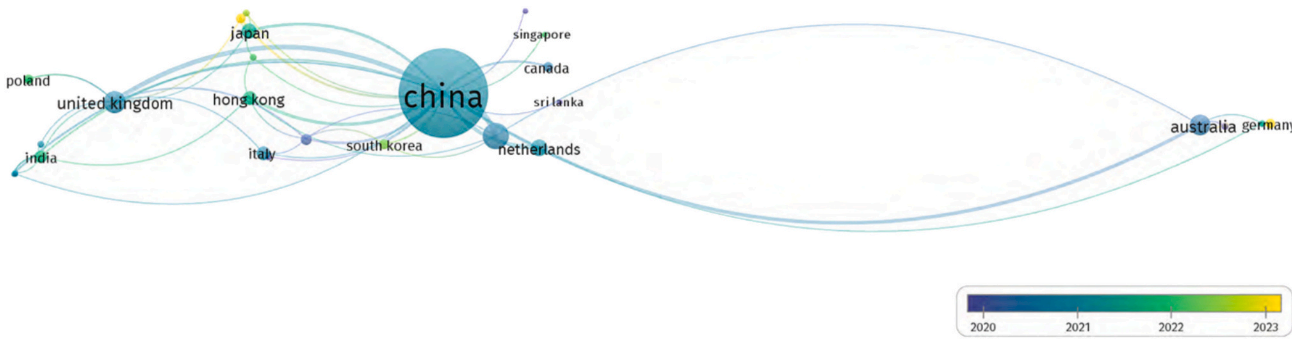


Fig. 1. Global collaboration network in Sponge City research.

arid-region settlements by minimizing evaporation and using gravity-fed transport. Beyond a technical solution, it shaped landscapes, structured communities, and reinforced local governance (Sanaan Bensi, 2020). Preserving Qanats today safeguards not just infrastructure but a living heritage of water, culture, and cooperation.

China's Sponge City initiative builds on historical precedents–from Qanats to floating gardens–advancing a shared logic: effective water management relies not on control but on adaptation, aligning urban rhythms with natural hydrological cycles (Zhang et al., 2019; Guan et al., 2021). Designed as hydrological systems that absorb, store, and

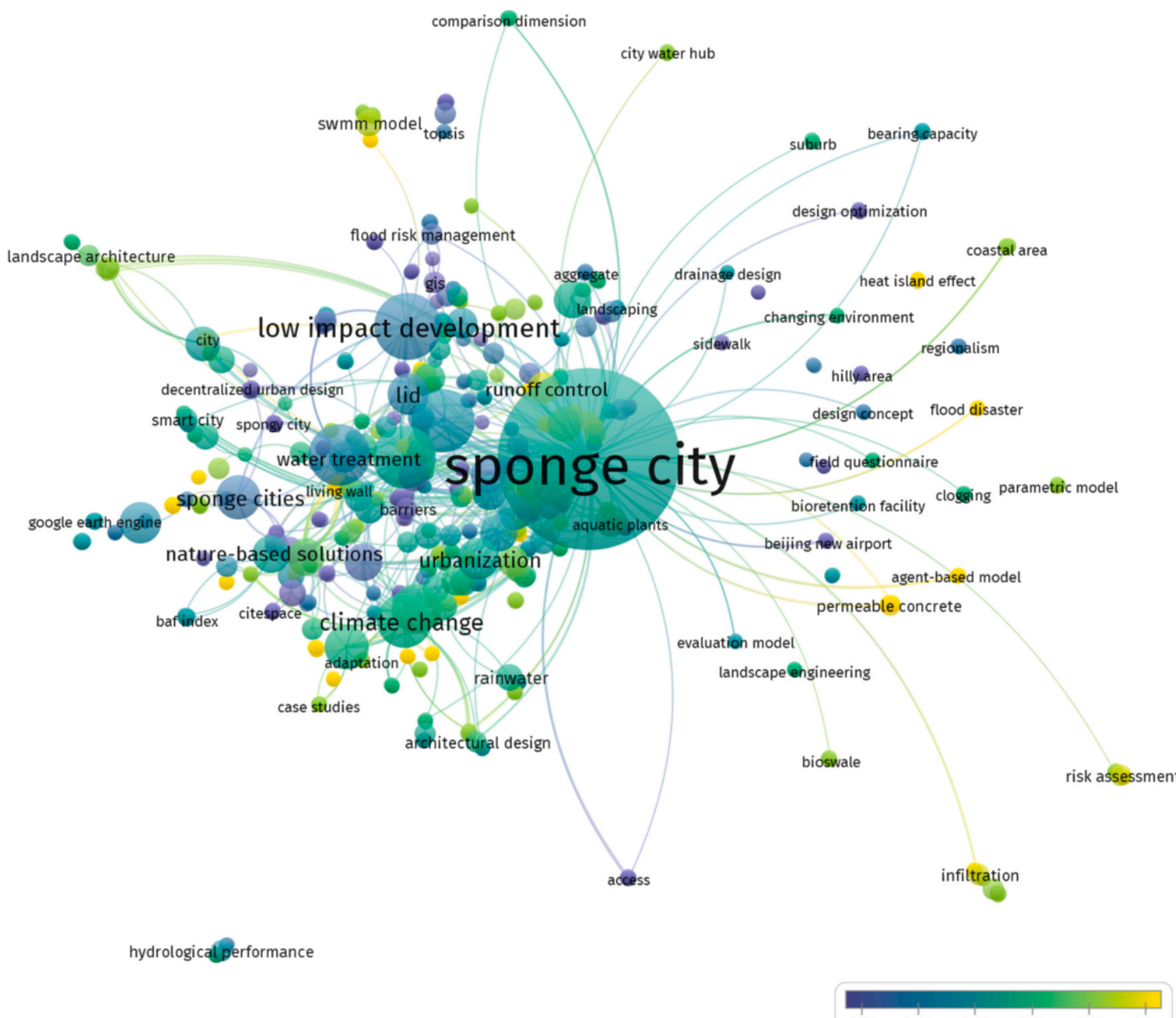


Fig. 2. Keyword co-occurrence network in Sponge City research (2019–2024).

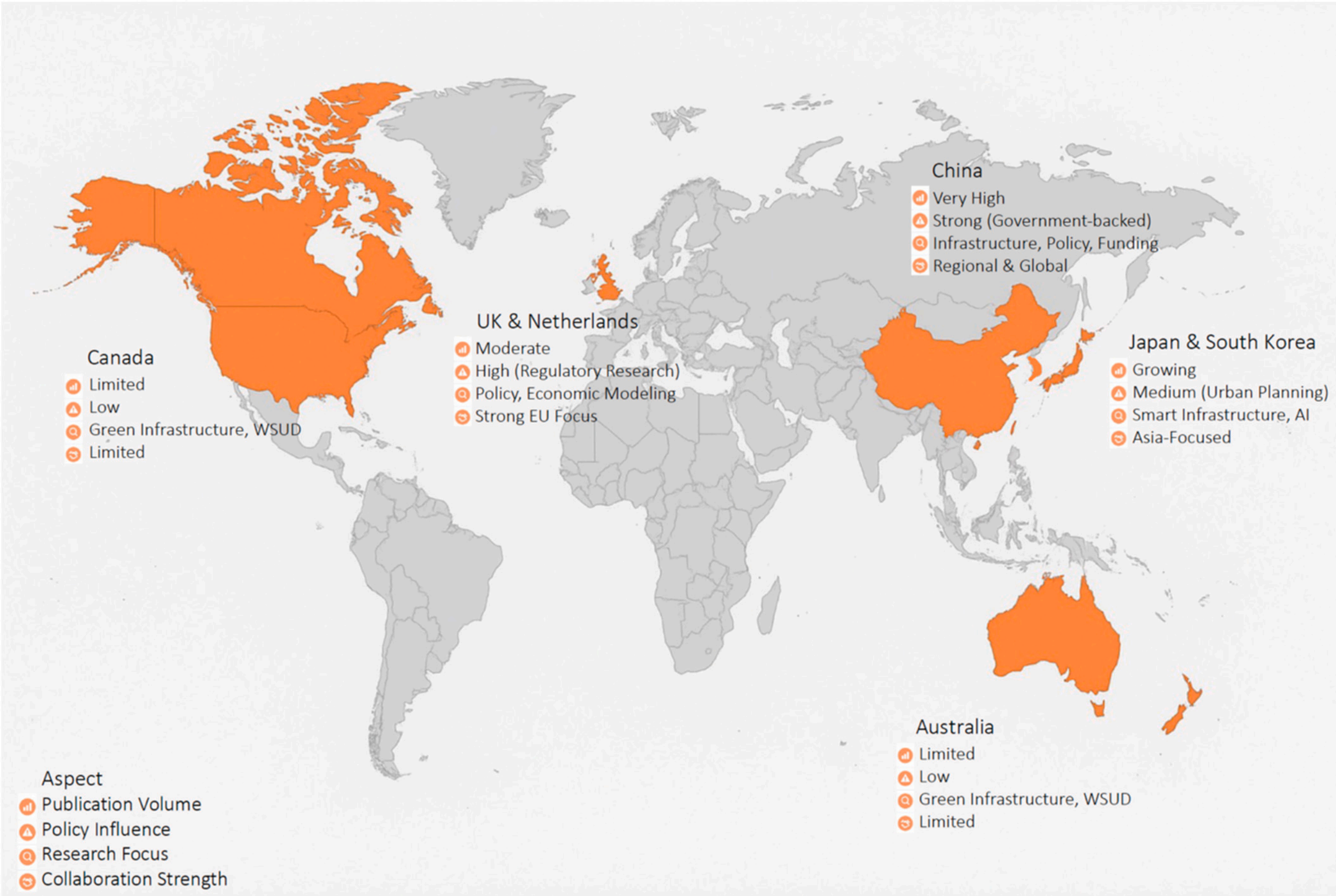


Fig. 3. Comparative analysis of research trends.

reuse rainwater, Sponge Cities enhance resilience by embedding the water cycle into urban form. More than technical solutions, they embody dynamic relationships between land, water, and society. This study explores how such principles are locally translated in the Netherlands, where global insights inform site-specific urban strategies.

This study illuminates how global strategies gain new meaning when ground the integration of global Sponge City strategies with Dutch urban adaptation efforts shows both alignment and departure–technical coherence, but also socio-spatial reimagination. At foundational level Dutch projects actively embrace well-known strategies from around the world: permeable surfaces, rain gardens, urban buffers, and green-blue networks. These reflect a strong alignment with the international approaches and their focus on ecological resilience and hydrological function. However, what distinguishes the Dutch cases is not the novelty of technical solutions, but their contextual layering. These interventions are reinterpreted through the lens of daily life–designed not only for stormwater management but also for accessibility, play, gathering, and care. Elderly residents, for instance, are not treated as a central actor in shaping inclusive public space.

This study illuminates how global strategies gain new meaning when grounded in place. They suggest that success lies not only in hydrological performance but also in the capacity to cultivate social inclusion, improve a sense of belonging, and ensure long-term urban livability. These highlight the need to recalibrate global frameworks–expanding their focus to include equity, community engagement, demographic resilience, and the shifting dynamics of urban public life.

1.2. Contributions of the study

This study advances Sponge City research and practice through three interrelated contributions:

Conceptually, it develops a cross-scalar, landscape-sensitive lens for understanding Sponge City strategies in Dutch lowland contexts and situates these insights in relation to international cases. By bringing typology and geography into dialogue, the study argues that Sponge Cities are not universal templates, but socio-ecological configurations shaped by place-specific material, institutional, and cultural conditions. It further extends prevailing technical-hydrological framings by explicitly foregrounding design, social inclusion, and spatial justice as core dimensions of adaptation in the Netherlands.

Methodologically, the study proposes a replicable classification of green, blue, and green–blue strategies linked to the four Sponge Basin principles (protect, delay, store, release). Applying this framework across both the global scan and the Dutch case studies moves the discussion beyond narrative descriptions or project catalogues and enables systematic cross-case comparison, assessment of the degree of integration, and future performance-oriented inquiry.

Empirically, the study documents the persistent gap between Sponge City theory and lived implementation in Dutch lowland contexts, especially regarding social inclusion, accessibility, and participation. Through thematic coding and cross-case analysis, it shows that many interventions operationalize only parts of the Sponge Basin principles and rarely embed equity, age-friendly design, or co-creation in a consistent and systematic way.

2. Literature review

2.1. Sponge Cities strategies across the world

China dominates Sponge City research, driven by government policies and large-scale urban infrastructure projects (Wu et al., 2023). It records the highest number of publications and collaborations, particularly with Hong Kong, Japan, South Korea, the UK, and the Netherlands (Wu et al., 2023). In contract to China's implementation-driven approach, Europe's approach is more theoretical, focusing on governance, sustainability, and economic models (Yu & Li, 2023). The Netherlands–with its long-standing expertise in water management, contributes expertise in flood management and policy frameworks, while Germany and the UK focus on sustainable urban planning and economic feasibility. However, Europe's direct involvement in Sponge City projects remains limited compared to China's large-scale urban experiments (Fig. 1).

Japan's research on Sponge Cities is heavily shaped by disaster risk, given the country's vulnerability to typhoons, heavy rainfall, and coastal flooding. Studies emphasize flood mitigation, resilient urban planning, and disaster recovery strategies, linking Sponge Cities to national risk reduction policies. Unlike China, where implementation is focused on urban expansion, Japan's research often seeks to integrate Sponge Cities into existing high-density metropolitan areas with limited space for large-scale modifications.

While uniform terminology can support clearer communication and knowledge exchange, the diverse terms used across regions also embodies local interpretations, enabling each country to adapt the concept to its unique context and priorities (Hawken et al., 2021) (Fig. 2). For instance, Japan and South Korea contribute through technological advancements, such as AI-driven flood prediction models and permeable infrastructure (Wu et al., 2023), while Australia and Canada focus on nature-based solutions and water-sensitive urban design (WSUD) (Cai et al., 2023).

While WSUD aligns with Sponge City principles, its implementation in Australia is more localized, centered on stormwater management rather than large-scale urban redevelopment. Canada participates primarily through policy and economic research, lacking large-scale projects. North America, particularly the U.S., is largely absent, reflecting different water management priorities (Yu & Wang, 2023). This lack of direct implementation projects suggests that Sponge City research in North America remains largely theoretical, rather than being driven by national policies or large-scale funding as in China.

The lack of long-term research and regionalized focus limit the broader adoption of Sponge City principles (Wu et al., 2023). Expanding global collaboration, integrating AI and smart technologies, and conducting long-term impact studies are essential for advancing the field beyond China-centric models (Wu et al., 2023) (Fig. 3).

2.2. Positioning design and society in Sponge Cities

Urban water management is one of humanity's grand challenges, acknowledged by key international frameworks including the Sustainable Development Goals (SDGs) (UN ESCAP, 2019) and the New Urban Agenda (UN Habitat, 2017). However, beyond infrastructural and technical ambitions, a key question arises: how are human dimensions–such as values, needs, and everyday experiences–incorporated into this transformation? Sponge Cities offer a promising response to climate-induced water stress, but their true impact lies not in theory, but in how they take shape on the ground–through landscapes, water flows, and people's everyday lives.

Sponge City design is more than an engineered response to water; it is a dialogue between land, water, and the people who inhabit these spaces. This study examines Sponge City design strategies across different landscape types in the Netherlands, using a small-N qualitative approach (Goertz & Mahoney, 2012) with a cross-case comparison. While large-N studies rely on statistical comparisons across many cases and generalization, small-N research allows for a context-sensitive analysis, tracing how ecological, hydrological, and social dynamics shape the success of blue, green, and blue-green strategies. By focusing on a limited set of case studies, this study does not aim for broad generalizations. Instead, it provides context-sensitive insights, offering perspectives that are embedded in place, shaped by context, and reflective of lived experience.

Design in this context is both outcome and process. As a noun, it refers to spatial interventions; as a verb, it denotes the act of envisioning and shaping future environments (Dilnot, 1982); Steinitz, 1995; Nijhuis & de Vries, 2019). Too often, design is reduced to physical form, overlooking its participatory and societal dimensions. These risks make discussions on design and society fragmented, reducing design to a technical function rather than recognizing it as an evolving, participatory process that reshapes the world we inhabit (Lera, 1981). As Lera (1981) argues, without acknowledging the human process of designing, we risk overlooking their role in influencing resilience, public space use, and socio-ecological interactions. In Sponge Cities, this extends beyond technical solutions to questions of accessibility, equity, livability, and long-term adaptability.

However, design is not just about creation–it is about continuity. In Sponge Cities, the success of strategies relies on multi-stakeholder governance setting (Van Montfoort & Lulofs, 2025). This means involving people not only during design but also in post-implementation for maintenance and adaptation. Active participation across phases ensures long-term functionality and allows interventions to evolve with ecological, social, and climatic changes. Design, then, becomes a collective, ongoing process that strengthens urban resilience and adaptability.

Despite growing research on climate resilience (Yu et al., 2025), the social performance of sponge strategies–how they respond to governance, equity, and everyday life–remains underexplored. A lack of engagement from design and social science disciplines further limits inquiry into lived urban dynamics (Hawken et al., 2021). The term ‘design-and-society’ thus captures both the tangible benefits of resilient infrastructures and the integration of social concerns into design thinking.

This study, therefore, asks: How do Sponge City strategies vary across different landscapes in the Netherlands and globally? What social dimensions emerge within these cases, and how do they reflect broader urban resilience principles? By exploring these questions through cross-case analysis, this research connects design theory with practice, exploring how Sponge Cities function as both environmental and social systems across diverse geographies.

2.3. Sponge Cities through lowlands

The Dutch lowlands are an artificial landscape, shaped by centuries of human intervention and an ongoing dialogue between land and water. Among the diverse landscape typologies of the Netherlands, five are lowland water: sand-ridge landscapes, river landscapes, peat grasslands, lake-bed polder landscapes and lake landscapes. Each of these landscape types is characterized by a specific water form (Bobbink & Leon, 2004), where hydrological processes plays a fundamental role in both their formation and continuous transformation. Their water networks–whether shaped by rivers, lakes, or peat marshes–demand constant maintenance and modification to remain resilient under environmental and climatic change.

The polder system, shaped by reclamation and drainage, reflects continuous adaptation. Each polder requires ongoing maintenance, embodying water's dual role as both a shaping force and a constant management challenge. In this context, urban development does not occur apart from the landscape, but as an extension of it, making water-sensitive design a spatial necessity rather than an optional layer.

The continuous interaction between the natural and the constructed, the urban and the landscape, remains a defining force in the evolution of Dutch cities. Many of the country's oldest urban centers are located within these lowlands, where integrating landscape characteristics into urban planning is most urgent. Here, water management is not only a technical necessity but also a spatial and design-driven challenge

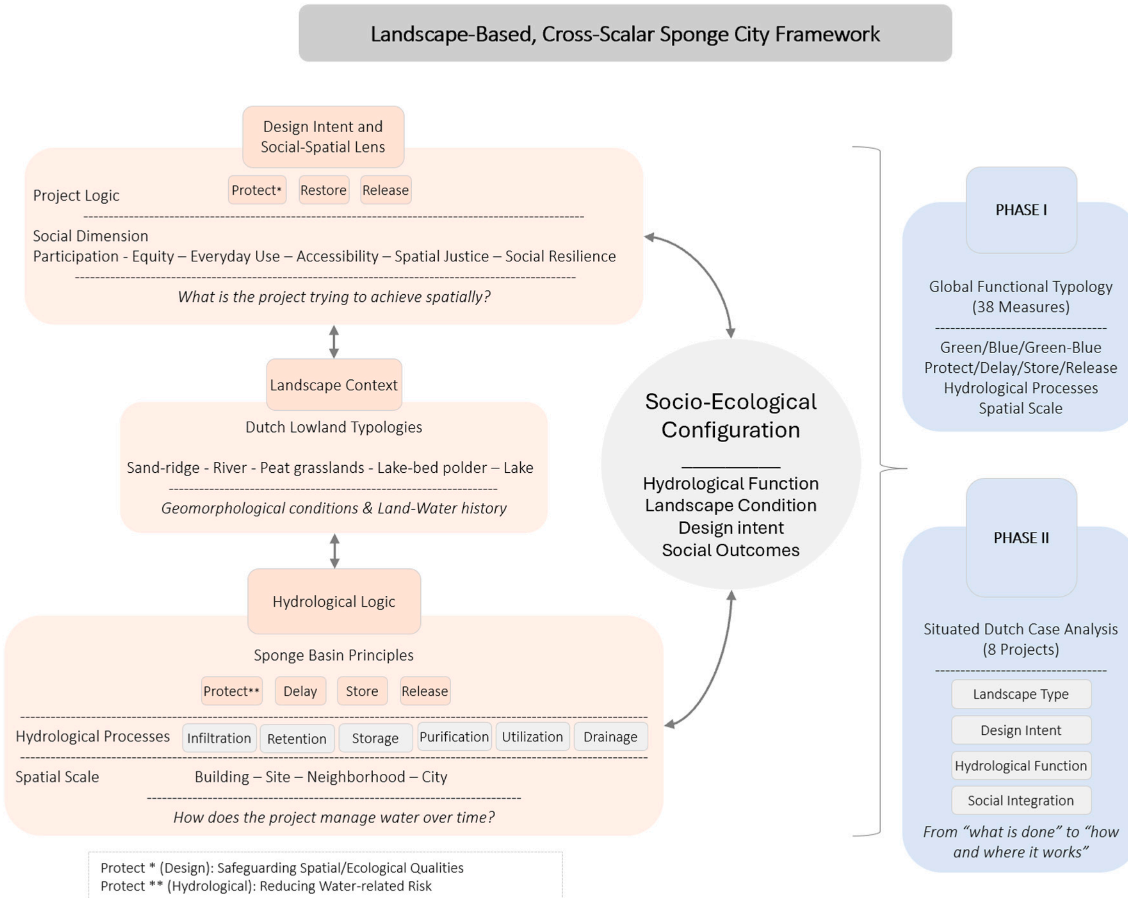


Diagram 1. Conceptual model of the landscape-based, cross-scalar Sponge City framework: The model integrates (1) project-level design intent and social-spatial dimensions, (2) landscape typologies as geomorphological conditioning contexts, and (3) Sponge Basin hydrological principles across spatial scales.

(Bobbink & Leon, 2004), reflecting a constant negotiation between the built and the natural environment.

This study intentionally focuses on case studies from these five landscape types, examining how Sponge City strategies interact with their distinct hydrological conditions. The selected projects are not chosen for their aesthetic appeal but for their capacity to illustrate the evolving relationship between Sponge Cities, landscape, and society. By situating these cases within a broader international comparison, the study highlights how local water management traditions and spatial adaptations contribute to global approaches to resilient urbanism.

Focusing on these landscapes allows for a structured and comparative analysis of their distinct hydrological conditions. Examining how do blue, green, and blue-green strategies perform across the five lowland water landscapes in the Netherlands, and how do they compare globally? Understanding these patterns is key to refining Sponge City design and making it adaptable across diverse urban and ecological landscapes. By identifying commonalities and differences, we can move beyond isolated projects to develop broader strategies for resilient, water-sensitive cities.

This study responds to these gaps through two levels of comparison. At the national scale, cases across the five lowland water landscapes make it possible to identify patterns and differences in blue, green, and blue-green approaches. At the case global scale, using a focused set of variables, evaluates sustainability and social impacts while highlighting the most promising opportunities for climate adaptation. Together, these perspectives provide deeper understanding into how Sponge City principles can be adapted to different landscapes and set the ground for the methodological framework discussed in the following section.

2.4. Theoretical framework: landscape-based, cross-scalar Sponge Cities

This study understands Sponge Cities not as a fixed set of techniques, but as socio-ecological configurations that emerge at the intersection of hydrological function, landscape form, and lived urban experience. Conceptually, the analysis is grounded in a landscape-based, cross-scalar Sponge City theoretical framework (Diagram 1) that systematically integrates three interrelated dimensions.

First, the Sponge Basin principles of protect, delay, store, and release (Biswas et al., 2019) provide a functional vocabulary to classify interventions by their hydrological roles. Rather than treating interventions as isolated catalogues of measures, these principles highlight which hydrological functions are emphasized or neglected, and how responsibilities are distributed across scales from site to city.

Second, the framework incorporates Dutch lowland landscape typologies: sand-ridge landscapes, river landscapes, peat grasslands, lake-bed polder landscapes, and lake landscapes (Bobbink & Leon, 2004); recognizing that each Sponge City intervention is a situated response to distinct land–water histories and geomorphological conditions. The landscape context is not treated as a neutral backdrops but as an active socio-ecological ground that conditions what sponge strategies can realistically achieve, and where they may fall short.

Third, a design-and-society lens frames Sponge Cities as more than technical hydrological infrastructures by foregrounding human dimensions (e.g., participation, equity, everyday use, and accessibility) as integral to climate adaptation outcomes. Building on debates on design as both process and outcome (Dilnot, 1982; Nijhuis & de Vries, 2019; Steinitz, 1995), this social-spatial perspective ensures that analyses consider how interventions support (or hinder) social resilience and

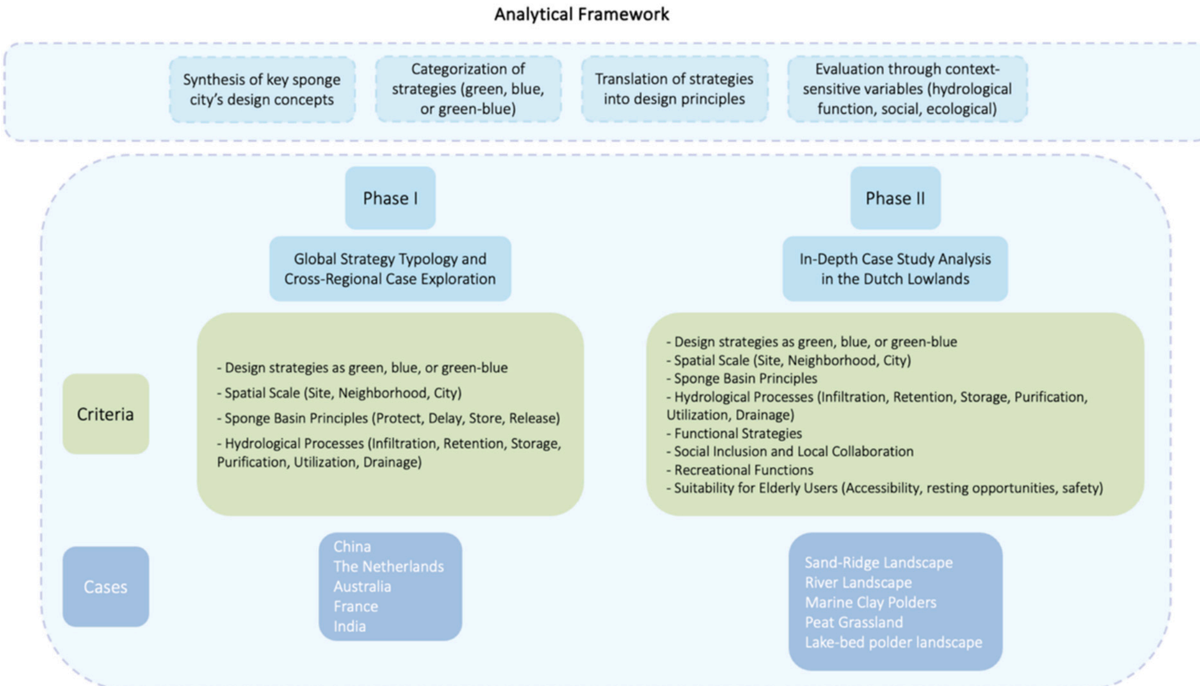


Fig. 4. Research Design process: outlining a two-phase methodology: (I) develops a global typology of Sponge City strategies through cross-regional case analysis; (II) applies in-depth evaluation in Dutch lowlands based on spatial scale, hydrological function, social inclusion, and design suitability).

spatial justice in practice. This perspective foregrounds participation, equity, everyday use, and accessibility as integral to climate adaptation rather than as secondary co-benefits. It enables the analysis to trace not only which physical measures are present, but how they support–or fail to support–social resilience and spatial justice in practice.

Crucially, these three dimensions are applied in a complementary, layered manner. At the project level, each case is interpreted through its design intent–what it aims to protect, restore, or create in its local context. At the same time, each intervention is evaluated by its hydrological function–how it protects, delays, stores, or releases water over time. This dual lens (design intent vs. hydrological function) uses similar terminology (both include a "Protect" phase) but at different conceptual levels. In a design-intent context, "Protect" refers to safeguarding spatial or ecological qualities; in a hydrological context, it refers to reducing exposure to water-related risks.

This distinction is maintained consistently throughout the study. The project-level framework (Protect / Restore / Create) captures design intent and spatial logic–why and how an intervention is conceived in relation to existing landscape conditions. The Sponge Basin principles (Protect / Delay / Store / Release), by contrast, describe hydrological performance–what the intervention does in managing water over time. The former guides the qualitative evaluation of each case in Phase II, while the latter supports cross-case comparison and is visualized in the comparative figures (e.g., Figs. 11–12). Aligning these perspectives reveals the extent to which technical measures and design goals coincide across different scales. Within this integrated framework, Phase I of the research constructs a global functional typology of Sponge City strategies, organizing 38 measures along the axes of: (a) green, blue, and green–blue configurations; (b) Sponge Basin principles (protect, delay, store, release); (c) hydrological processes (infiltration, retention, storage, purification, utilization, drainage); and (d) spatial scale (building, site, neighborhood, city). In Fig. 9, building-scale measures are operationalized within the site category because, in implementation and reporting, they are typically delivered as components of integrated plot/block/site systems. By contrast, in Fig. 5, building-level interventions are retained as a distinct category because they are more consistently described in the literature as discrete building-specific strategies and are analytically useful to show separately in the global typology.

Phase II applies this typology to Dutch cases, reinterpreting eight projects through the lens of lowland landscape types and examining the degree of integration between hydrological intent, landscape logics, and social concerns. This phase examines each project through the combined lenses of its landscape type, hydrological intent, and social design considerations. This two-phase cross-scalar approach shifts the study from a global overview of "what is done" to a situated reading of "how and where it works" in the Dutch lowlands, and where gaps remain between theoretical ambition and lived implementation.

3. Method

This study adopts a qualitative, descriptive case study methodology within an interpretivist paradigm to explore how Sponge City strategies support urban climate adaptation. Anchored in the landscape-based theoretical framework outlined above, it focuses on the spatial, ecological, and social dimensions of Sponge City strategies across diverse landscape types and climatic contexts. Given the inherent complexity of Sponge City interventions–where hydrological, spatial, and social processes intersect–a multi-scalar, comparative approach was necessary to capture both localized adaptations and broader systemic patterns. The study seeks to understand how design strategies are implemented in context and how they align with wider goals such as hydrological resilience and social inclusion.

The analysis concentrates on the spatial configuration and strategic alignment of Sponge City interventions rather than on modeling or monitoring their hydrological performance. While the cases do incorporate hydrologic functions such as infiltration, retention, storage, purification, utilization, and drainage, quantitative indicators (e.g. event-based retention volumes or peak-flow reductions) are inconsistently reported and not directly comparable across projects. These functions are therefore treated qualitatively, as proxies for how different strategies operationalize the Sponge Basin principles, and quantitative performance assessment is explicitly positioned as an important next step rather than the primary aim of the present study.

To strengthen the validity of qualitative claims in the absence of comparable quantitative metrics across countries, this study ensured qualitative rigor through triangulation of data sources, rule-based classification of strategy types, and peer debriefing. These measures strengthen the validation of claims, without relying on standardized numerical indicators.

3.1. Research design and case selection

The study combines within-case and cross-case comparative analysis (Gerring, 2007; Yin, 2003), enabling deep contextual insight while identifying patterns and shared challenges across cases. Cases were selected through information-based sampling (Wandl, 2020), aimed at maximizing variation in landscape type, climate, urban scale, and cultural setting. The key criteria guided case selection are: (a) Representation of diverse climatic contexts, and (b) Availability of sufficient documentation (e.g., spatial plans, policy reports, evaluations). The population of cases spans projects in the Netherlands, China, Australia, France, and India, allowing for a comparative reading of how Sponge City strategies are interpreted and adapted globally (Hawken et al., 2021).

3.2. Analytical framework

A structured four-step analytical framework was developed to guide the research (Fig. 4), directly following the theoretical lens introduced in Section 2.4. This study adopted a document-based, qualitative approach, grounded in a layered analysis of literature, municipal planning documents, urban design reports, and academic policy frameworks. The research included two phases: Phase I constructed a global functional typology of strategies; Phase II reconsider Dutch Sponge City projects within the five lowland landscape types using thematic analysis.

3.2.1. Phase I: global strategy typology and cross-regional case exploration

This phase focused on tracing consistencies and divergences across international contexts, establishing a reference set of design interventions. Within the landscape-based framework, this phase establishes the functional "space" of Sponge City design by mapping how different projects combine green, blue, and green–blue configurations with Sponge Basin principles and hydrological processes across spatial scales. In this phase, a global scan of Sponge City-related design strategies was conducted to build a comprehensive typology of these strategies. This typology is grounded in literature review and document analysis of selected projects from five countries: China (, the Netherlands, Australia, France, and India.

A total of 38 design strategies were identified and categorized as green, blue, or green-blue, based on their primary environmental function. The aim was exploratory to collect a broad, representative set of strategies situated internationally in contexts where the concept of Sponge Cities, WSUD, or similar hydrological planning practices are strongly part of design discussions.

The selection of strategies did not have a formalized evaluation framework with predefined inclusion/exclusion rules; however, it followed a consistent exploratory logic prioritizing spatially explicit interventions across scales, functionality, and hydrological processes. The aim was to collect a broad, representative set of strategies situated internationally in contexts where the concept of Sponge Cities, WSUD, or similar hydrological planning practices are strongly part of design discussions. Taking into consideration the available time and scope of the research, a diverse number of cases were surveyed from different regions. When it comes to excluding strategies, the methodology lies in omitting non-spatial interventions and purely hard infrastructural designs.

To distinguish green, blue, and green–blue strategies, the typology applies simple rule-based criteria rather than ad hoc visual judgements. Green strategies are interventions where stormwater is managed primarily through vegetated soils and permeable surfaces (e.g., parks, rain gardens, green streets), without a dedicated open water body or engineered basin as the dominant element. Blue strategies are those where water is mainly handled by open water or engineered storage and conveyance (e.g., canals, retention basins, tanks) with only marginal vegetation. Green–blue strategies intentionally combine both, coupling a vegetated soil profile with a designed storage or conveyance component such as a basin, pond, tidal edge, or controlled retention layer. Subsurface drains or minor outlet structures do not, by themselves, shift a measure from green to green–blue; reclassification requires that the engineered storage or conveyance plays a central role in the design. The same rule-based classification was applied when coding the Dutch cases in Phase II.

To increase transparency and comparability across countries, the global strategy inventory is fully presented in Appendix 2. The appendix also indicates which strategies appear across the country datasets summarized in Fig. 6.

3.2.2. Phase II: Dutch lowlands case studies

This phase analyzed eight projects in five Dutch cities, selected to represent the country's distinct lowland landscape types: sand-ridge landscapes, river landscapes, peat grasslands, lake-bed polders, and marine clay polders in Amsterdam, Rotterdam, Almere, Purmerend, and The Hague. Within the broader framework, these lowland types function as analytical lenses that link hydrological risk, and landscape form. These cases were selected using purposive sampling to ensure variety in five lowland types (e.g., river landscapes, marine clay polders) and adaptation strategies.

The case selection process was based on keyword inquiries in scientific and non- scientific search engines to identify cases; and a set of five screening criteria that defined suitability of cases for this study. A five-step screening procedure then narrowed this set to the final eight cases (Appendix 4): (1) relevance to sponge/Sponge City principles; (2) location within one of the five lowland landscape types; (3) appropriate intervention scale (building, site, or neighborhood); (4) availability of sufficient public documentation; and (5) recency of the main plans (< 15 years). In the next steps cases were excluded for wrong geographical location regarding lowland landscape types ($n = 24$); wrong scale ($n = 6$); insufficient documentation ($n = 4$).

This second layer of analysis applies the global functional typology developed in Phase I to Dutch cases, allowing the study to assess how Sponge City design strategies align not only with hydrological performance, but also with principles of social equity and age-friendly city planning.

In this Phase, case study data from the Netherlands were manually coded in ATLAS.ti and examined through cross-case comparison. Thematic coding allowed for the identification of patterns, context-specific responses, and the degree to which socially inclusive design was embedded, or absent.

Particular attention was given to the relationship between theory and implementation: How do the principles of Sponge City design manifest in lived environments? Where do they align with local needs, and where do they fall short? This layered approach enabled a cross-scalar understanding of Sponge City strategies—not only as environmental infrastructures but as socially embedded spatial practices. In the Dutch cases, this meant unpacking the ways in which ecological intentions intersect with spatial form, policy culture, and the everyday use of space.

In the global scan, the focus was on comparative mapping–tracing how strategies recur or diverge across contexts. In the Dutch cases, coding centered on how these strategies materialize within specific landscapes, governance cultures, and urban forms. In this way, Phase II "tests" the functional space defined in Phase I against the situated realities of the Dutch lowlands.

Moreover, to assess the degree of integration in each Dutch case, the study operationalized "integration" along two dimensions: (1) the presence of the four Sponge Basin principles (protect, delay, store, release), and (2) the configuration of green, blue, and green–blue strategies. For each project, ATLAS.ti codes were used to identify whether a given principle or strategy type was absent (0), partially implemented with only one or two independent principles/strategies (1), or extensively implemented with more than two interconnected strategies that reinforce each other (2), based on the documented design strategies and visual material (list of examined materials per case can be found in the Appendix 1). We then compiled these binary values into a cross-case results table, summarizing the share of fulfilled versus missing functions per project and across the Dutch sample. This follows calls in the green infrastructure and Sponge City literature to evaluate multifunctionality and systemic integration through explicit criteria rather than narrative description alone.

3.3. Threats to validity and scope of generalization

This study uses a small-N, secondary-source, qualitative comparative design to position Sponge City strategies across international contexts and Dutch lowland landscape types. The aim is to identify design logics and recurring gaps between technical and social dimensions, rather than to claim statistical generalizability or rank national performance. The findings should therefore be read as analytically transferable insights that inform design reasoning.

Several limitations shape this scope. Selection bias may occur because well-documented or internationally visible projects are more likely to be included. Documentation bias is also expected, given uneven reporting depth and emphasis across countries and project types. Spatial heterogeneity across landscape conditions and governance arrangements means similar strategies may be configured and experienced differently. Finally, temporal change matters because cases vary in maturity and climate and policy baselines continue to evolve.

A follow-up study could adopt a mixed-methods, evaluation-oriented design combining longitudinal hydrological monitoring with site-based spatial/accessibility audits and resident surveys. This would allow the comparative patterns identified here to be tested across a broader empirical base and would link measurable performance with lived experience, maintenance dynamics, and equity outcomes.

4. Discussion

Sponge Cities, often framed as hydrological responses to climate risk, are in practice socio-ecological systems that unfold through infrastructure, landscape, temporality, and lived experience. This Small-N study does not seek statistical generalizability, but offers situated, layered insights into how sponge strategies are embedded in the spatial and socio-ecological fabric of the Dutch lowlands (Goertz & Mahoney, 2012). By tracing interventions across diverse landscape typologies, the research reveals how sponge principles are shaped–and sometimes limited–by local ecologies, planning frameworks, and everyday urban life. While these localized readings cannot be scaled uncritically, they offer design-relevant knowledge for policymakers and urban practitioners seeking more grounded, inclusive approaches to climate adaptation, and for rethinking Sponge Cities as context-sensitive, socially negotiated projects rather than purely technical solutions. Future studies might expand with large-N or mixed-methods approaches, yet the depth offered here is essential for understanding Sponge Cities as evolving, place-based negotiations between water, land, and society.

4.1. Phase I: situating Sponge City projects globally

4.1.1. Lack of social dimension in understanding of Sponge Cities

Despite technical successes, Sponge City initiatives often overlook social dimensions–including public participation, social equity, community resilience, and displacement–even though recent studies emphasize the need for timely and strong publicity alongside technical performance metrics (Wang & Palazzo, 2021; Wang et al., 2021; Li et al., 2026a). This gap calls into question the long-term sustainability and inclusiveness of such projects. Growing evidence suggests that long-term performance depends not only on engineering outputs but also on social legitimacy, co-management capacity, and risk communication.

In Chinese pilot cities, public meetings typically take place only after major plans are finalized, limiting local voices and contributing to mistrust. This top-down approach creates tension within communities, particularly when new infrastructure is introduced into neighborhoods lacking awareness or acceptance of these interventions. This dynamic influences stewardship, maintenance, and the everyday meaning of adaptive infrastructure. International examples further show the value of inclusive public participation for achieving both technical and social goals (Wolch et al., 2014). In Philadelphia's *Green City, Clean Waters program*–though not formally termed a Sponge City–co-production with citizens in selecting sites for rain gardens and green roofs shows a contrasting, more participatory framework than the technocentric implementations found in several Chinese cities. Participation, in this sense, operates not merely as consultation but as a mechanism through which technical systems acquire social durability.

Infrastructure alone does not ensure resilience. Many projects lack local knowledge, training, and citizen-led maintenance, fail to engage vulnerable communities in co-producing interventions, which undermines community capacity to manage risk (Kibii et al., 2025). Moreover, retrofits can trigger property speculation (Haase, 2025) and community destabilization. Embedding social considerations in these initiatives requires participatory governance, equity assessments, community education, and anti-displacement policies. Without training, risk communication, and preparedness, residents may remain vulnerable even when surface flooding is reduced (Fu et al., 2023).

Distributional equity further raises questions about who benefits from Sponge City interventions and whether marginalized communities receive adequate flood protection or improved water quality. In many pilot projects, priority sites for Sponge City investments are often high-profile commercial districts or new development zones, while low-income or informal neighborhoods remain reliant on outdated drainage systems (Ding et al., 2019). Such priorities risk deepening existing inequalities.

At the same time, some Sponge City plans often lack recognition and procedural equity: they fail to consider the specific needs of vulnerable groups or involve them meaningfully in decision-making. Without understanding local contexts–cultural practices, mobility constraints, or traditional coping strategies–new amenities may be inaccessible or lead to displacement through green gentrification and related environmental justice dynamics (Anguelovski et al., 2022). These justice dimensions shape whether interventions are experienced as accessible, legitimate, and worth maintaining over time.

Local knowledge–for instance, in identifying flood-prone hotspots or cultural sensitivities–can significantly improve the design and maintenance of Sponge City facilities (Ding et al., 2019). When projects integrate local expertise (e.g., through co-management or citizen-monitoring initiatives), community members develop a sense of ownership that supports maintenance and strengthens social networks. In this sense, local knowledge and co-management function as both technical assets and social infrastructure. Early signs of green gentrification and displacement linked to Sponge City projects are already evident in rapidly urbanizing regions of China (Jiang et al., 2018). While official rhetoric presents Sponge Cities as comprehensive solutions for flood management and livability, certain redevelopment plans lack affordable housing and tenant protections (Ding et al., 2019). Paradoxically, successful interventions–manifested in improved public spaces such as lakeside parks and wetlands–can coincide with rising housing costs and socio-economic upscaling (Sánchez et al., 2026). These dynamics can catalyze green gentrification, whereby wealthier buyers and commercial interests displace lower-income residents. Without these safeguards, Sponge City schemes risk entrenching social divisions and leaving vulnerable groups under-served and exposed to

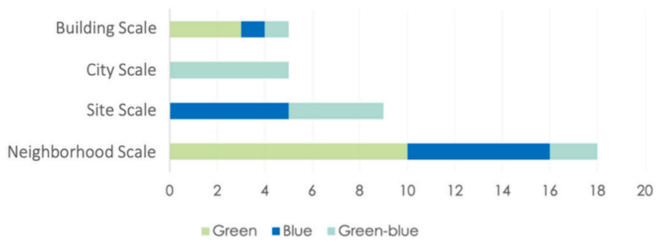


Fig. 5. Design strategies by scale.

residual flood risk rather than eliminating it (Wang & Palazzo, 2021)–undermining the very social fabric that is essential to community resilience (Lu et al., 2025).

4.1.2. Navigating the scale paradox in Sponge City design

Although Sponge City theory promotes decentralized, building-level interventions like green roofs and permeable pavements, practice shows a shift toward neighborhood-scale implementations where blue and hybrid systems dominate (Fig. 5). This moves from modularity to consolidation reflects a pragmatic turn, favoring centralized systems for their broader hydrological impact and easier management. Notably, this often leads to misguided applications, such as green roofs in arid regions with acute water scarcity (Rabbani et al., 2022), while dense urban cores remain largely underserved.

Neighborhood-scale projects align better with planning frameworks, funding mechanisms, and management structures, offering visibility and efficiency. In contrast, building- and buffer-level strategies remain mostly on paper, hindered by fragmentation and weak stakeholder engagement. Their marginalization raises questions about the scalability and institutional support for decentralized approaches.

This analysis highlights a critical tension between the theory's modular vision and the realities of cost, governance, and infrastructural inertia, which tend to favor large-scale, high-impact projects. What drives this preference for certain scales? And what is lost when smaller, socially embedded interventions are sidelined?

As Sponge Cities evolve, understanding these choices is key–not only for hydrological performance, but for the ways they shape urban experience, agency, and resilience. This motivates Phase II's closer examination of how governance arrangements and landscape conditions shape cross-scalar coherence in implementation, and what policy incentives might enable distributed strategies to move beyond paper.

Fig. 5 presents the distribution of Sponge City strategy types (Green, Blue, and Green–Blue) across four spatial scales, based on 79 total cases included in the review. The number of cases per strategy category is: Green ($n = 23$), Blue ($n = 28$), Green–Blue ($n = 28$). The figure illustrates how frequently each strategy type appears within neighborhood, site, city, and building-scale interventions, enabling cross-scalar comparison of adoption patterns. *Note: Scale is represented using four distinct categories (building, site, neighborhood, city) to preserve the full typological gradient.*

A qualitative overview of how Sponge City strategies are distributed across the countries represented in the 79 cases (Fig. 6). Each marker indicates the presence of a Green, Blue, or Green–Blue strategy in at least one documented case in that country. This analysis interprets data trends to identify the most adopted design strategies, highlight regional differences and priorities, and assess their strengths, limitations, and broader implications. It offers a critical perspective on how theoretically grounded Sponge City measures are adapted in practice across Asia, Europe, North America, and beyond.

4.1.3. Widely adopted strategies

The analysis of Sponge City strategies across countries (Fig. 6) reveals a layered terrain–an interplay between local innovation, global diffusion, and infrastructural priorities. Among the 38 strategies, 13 are rooted in the Netherlands, where experimental approaches like multi-functional systems illustrate a design culture integration and innovation. China follows closely with 15 strategies, characterized by top-down pilot

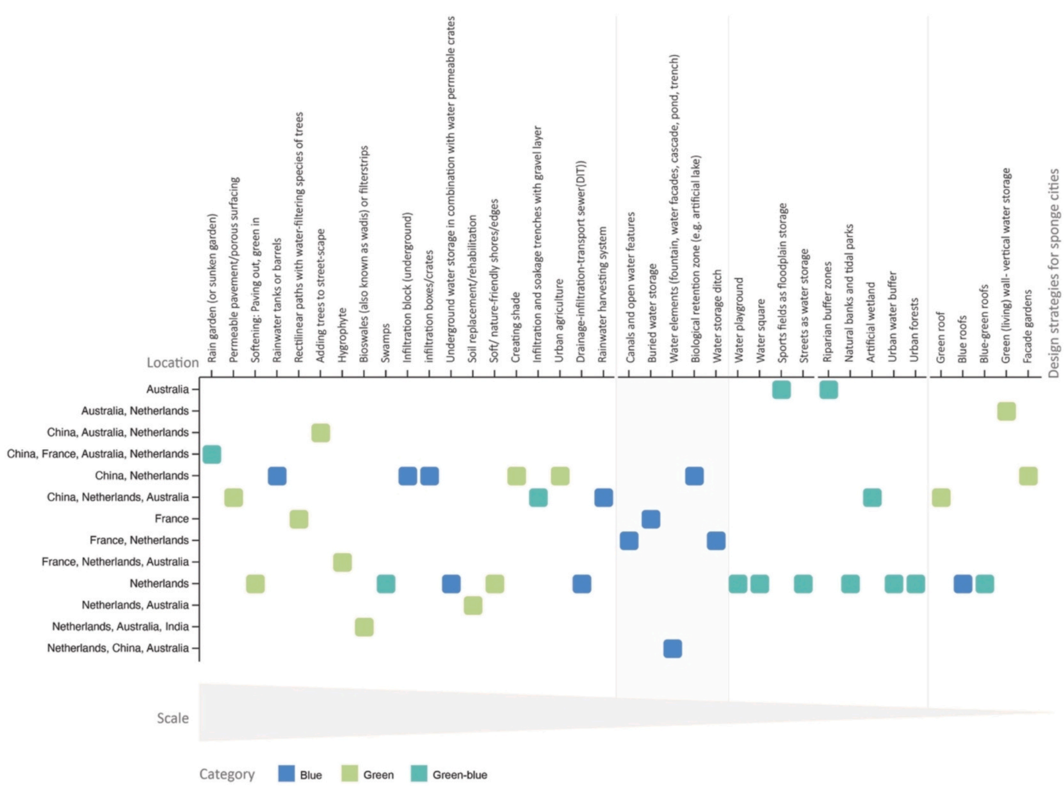


Fig. 6. Design strategies by country: China (Chen et al., 2021; Yu, 2021), the Netherlands (Programmakader WeerWoord 2030), Australia (Lewis et al., 2015), France (ICI Consultants, 2015), and India (Biswas et al., 2019).

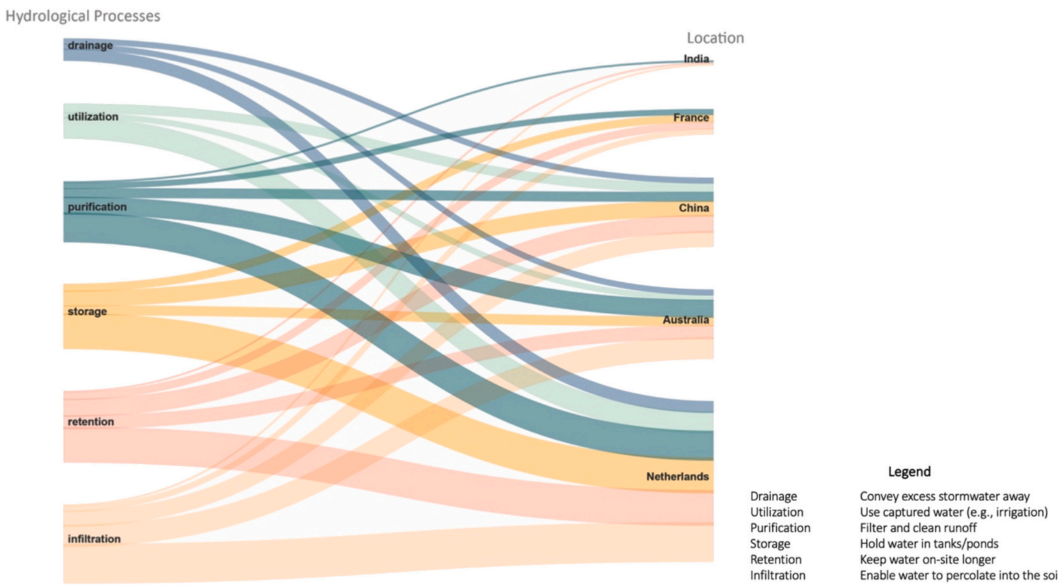


Fig. 7. Global Distribution of Hydrological Processes in Sponge Cities.

projects emphasizing engineered, measurable outcomes. Australia, with 14 strategies, reflecting a pragmatic blend of function and form. In France, the focus leans toward blue infrastructure–reflecting a more engineering-driven approach to managing water in the city. India, represented by a single strategy–bioswales–implying either a limited adoption or limited documentation of Sponge City measures there.

A few design strategies appear across multiple regions, suggesting a core toolkit. Rain gardens (bioretention basins) stand out as the most widespread, implemented in China, France, Australia, and the Netherlands. Green infrastructure elements like permeable pavements, rain gardens, bioswales, and green roofs–their widespread adoption reflects a global consensus on ecological and cost-effective value. It reflects not only ecological versatility but also their alignment with broader frameworks such as Sustainable Drainage Systems (SuDS) and Water Sensitive Urban Design (WSUD), which prioritize infiltration, retention, and evapotranspiration (Griffiths et al., 2020). These strategies have become the backbone of Low-Impact Development (LID), adaptable across climates and cultures.

In contrast, context-specific innovations–like water squares or tidal parks–tend to remain local, limited by technical complexity, cost, or unique hydrological conditions. Their constrained diffusion raises questions about the scalability and equity of innovation in Sponge City design.

France and Australia also show context-specific responses: infiltration boulevards and buried storage tanks shape the French approach, while Australia reimagines multifunctional landscapes–sports fields that double as flood zones–where resilience merges with daily life.

4.1.4. Theory vs. practice

The theoretical foundations of Sponge City design advocate for an integrated, multi-scalar approach–where blue and green infrastructures cross scales. However, the translation from concept to implementation often reveals gaps and tensions. Globally, the evidence suggests that integration is uneven and mediated by governance capacity, institutional path dependencies, and landscape constraints. In the Netherlands, the theory is closely approximated, with design strategies coherently stitched across spatial levels–from rooftop gardens to street-level swales and district-scale retention systems. China, by contrast, prioritizes quantity over integration. Australia, shaped by its arid climate, leans into vegetative and cooling strategies, while China responds to floods with large-scale underground storage. Local conditions–soil composition, population density, urban form–inevitably shape the edges of what is feasible, reminding us that Sponge City principles are always mediated through context.

4.1.5. Scaling Sponge Cities

Multi-level integration–across the building, street, neighborhood, district, and watershed scales–is often uneven. The Netherlands offers a rare example of full-spectrum integration. In contrast, China and Australia illustrate partial implementations, where specific scales remain disconnected. Identifying and addressing these spatial gaps becomes important if Sponge City initiatives are to deliver resilience, rather than fragmented performance.

At the hydrological level, this overview illustrates how countries apply hydrological processes–such as infiltration, retention, storage, purification, utilization, and drainage–within Sponge City frameworks (Fig. 7). Water management strategies vary by context: some prioritize engineered drainage, while others integrate water into daily life, viewing it as an asset rather than a threat.

While infiltration, retention, and storage form the backbone of urban water management, their implementation varies. The Netherlands and China employ a broad range of interventions, reflecting their long-standing engagement with water-sensitive planning, whereas countries like Australia and India focus on specific processes, likely shaped by climate conditions and regulatory frameworks. Importantly, Sponge City principles rely on interactions between processes–where infiltration supports retention, and storage facilitates reuse–yet these interdependencies are often overlooked in static representations.

Moreover, the geographical scope of this analysis remains limited, omitting regions that may offer alternative models, like South America's flood-adaptive urbanism or Africa's water-harvesting landscapes. Sponge Cities are more than a collection of techniques; they represent a dynamic relationship between land, water, and society. A more integrated approach is needed to move beyond simple mappings of strategies and toward a deeper understanding of how cities evolve in rhythm with their natural hydrology.

4.1.6. Hydrological processes and sponge basin principles

In analyzing the strategies, and based on Biswas et al. (2019), this study organized measures according to four core sponge-city principles: Protect, Delay, Store, and Release. (a) Protect refers to the conservation and restoration of existing urban green spaces and water bodies, preventing encroachment, degradation, and pollution to maintain ecological integrity. (b) Delay aims to reduce peak runoff during storm events

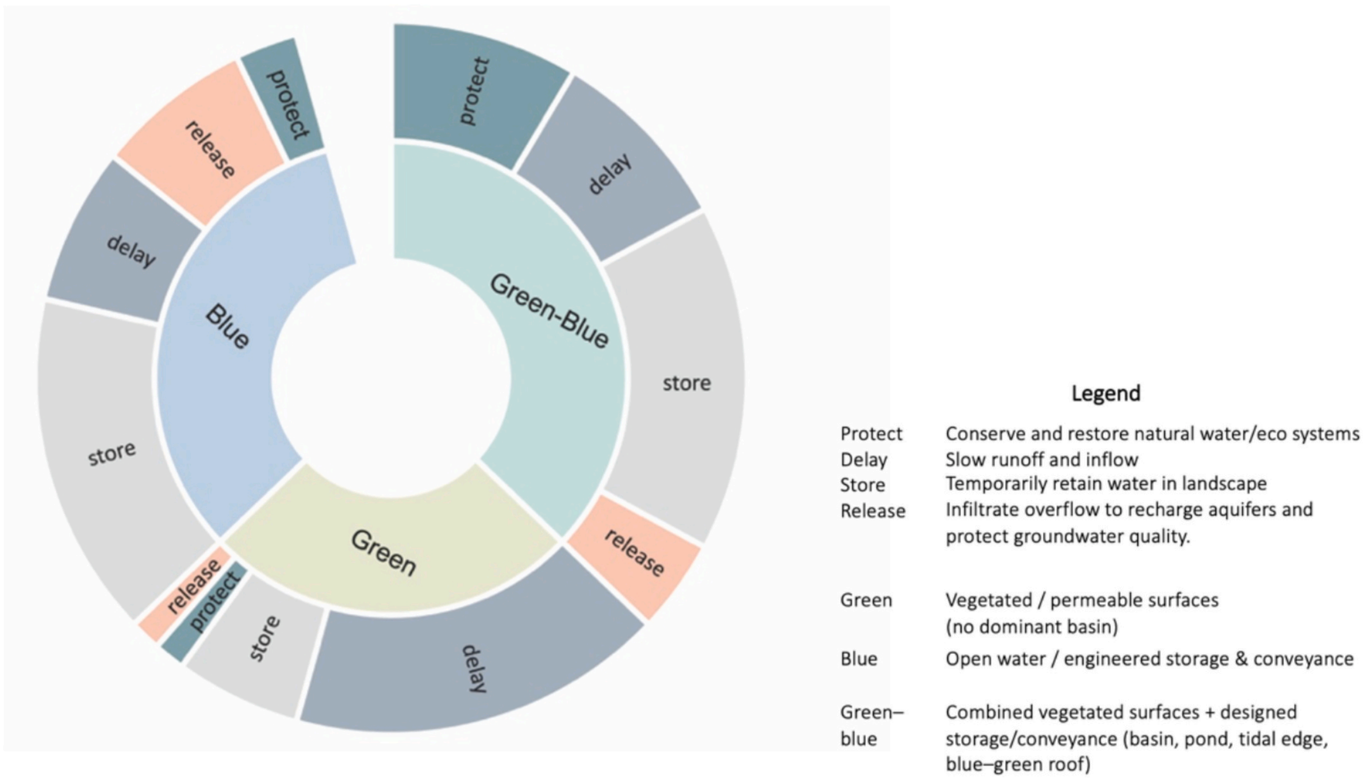


Fig. 8. The distribution of Sponge Basin Principles (protect, delay, store, release) across Green, Blue, and Green-Blue Sponge City strategies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

by slowing the movement of rainwater through the landscape; natural ground cover, vegetation, trees, and topographic variation increase lag time and help prevent drainage networks from being overwhelmed. (c) Store focuses on capturing and retaining water from intense rainfall for later use, thereby reducing water-scarcity risks through distributed systems such as rainwater harvesting, micro-reservoirs, tanks, and holding ponds near places of demand. (d) Release concerns the controlled management of surface water to allow safe infiltration and aquifer recharge while preventing contamination, including the protection of recharge zones, the management of overflows from storage systems, and the safeguarding of groundwater quality to avoid land subsidence and saltwater intrusion.

Fig. 8 visualizes the distribution of Sponge Basin Principles (protect, delay, store, release) across different Sponge City strategies (Green, Blue, and Green-Blue). While it provides a structured view of how hydrological functions are categorized, certain aspects merit critical reflection. The dominance of Delay and Store suggests a strong emphasis on water retention and management, yet the lesser representation of Protect and Release raises questions about the balance between flood mitigation, ecological preservation, and controlled water discharge. This functional imbalance suggests that ecosystem safeguarding and controlled release–often critical at larger landscape scales–are less consistently operationalized in documented interventions.

The marginal role of Protect reflects a recurring disconnect between ecosystem safeguarding and infrastructure-driven water management. While the Green-Blue category appears well-integrated, the separation

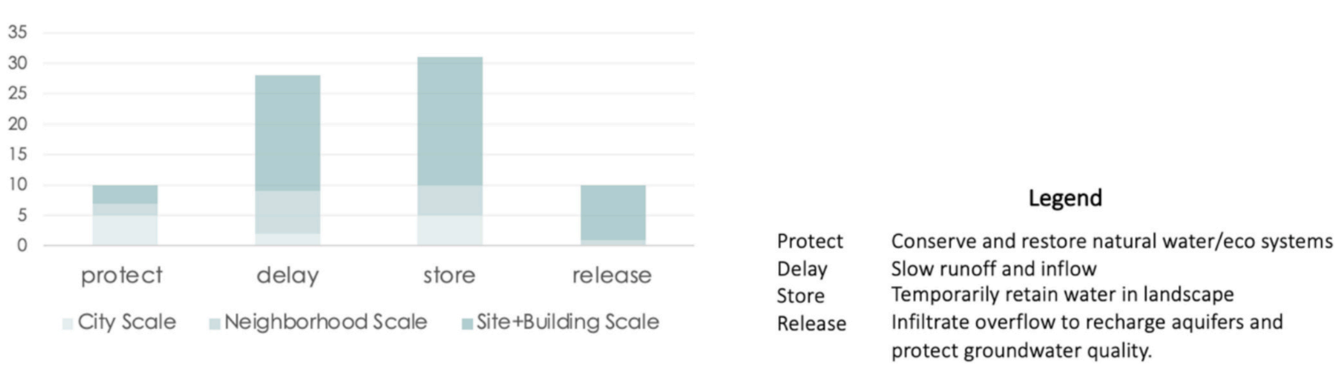


Fig. 9. Distribution of Sponge City strategies (protect, delay, store, and release) across site, neighborhood, and city scales, highlighting the predominance of small-scale interventions and the gap in large-scale implementation. *Note: Here, building-scale measures are included within the site category (three-level operationalization: site [incl. building], neighborhood, city) to reflect implementation/reporting practice and reduce false precision. Taken* together, Phase I establishes a global functional typology and identifies recurring patterns in how Sponge City strategies are assembled: a dominance of Delay and Store logics, uneven cross-scalar integration, and selective operationalization of Protect and Release principles. While social dimensions–participation, equity, and long-term stewardship–are acknowledged in theory, their institutional embedding remains inconsistent and highly context-dependent. These findings highlight specific structural tendencies: consolidation at neighborhood scale, technical prioritization over social co-management, and partial integration of hydrological processes.

Table 1
LowLands projects, categorized by landscape type, project location, type of city, and spatial scale.

Landscape Type	City	Project	Type of City			Scale		
			Coastal	Delta	River	City	Neighborhood	Site
Sand-Ridge Landscape	Den Haag	Nieuw-Binckhorst	■				■	
River Landscape	Rotterdam	Climate Proof Zomerhofkwartier		■	■		■	
	Rotterdam	Benthemplein Water Square		■	■			■
Marine Clay Polders	Rotterdam	Tidal Park Keilehaven		■	■			■
	Den Haag	Zuiderpark	■				■	
Peat Grassland	Amsterdam	Smart blue-green roofs			■	■		
Lake-bed polder landscape	Almere	Climate Proof Regenboog		■	■		■	
	Purmerend	Waterlandkwartier		■	■		■	

of green and blue strategies may oversimplify the multifunctional and often hybrid nature of real-world interventions–where these elements often overlap. Furthermore, the diagram illustrates a gap between theory and practice–where the theoretical comprehensiveness of Sponge Cities is not always matched in practice (also mentioned by Li et al., 2017), as implementation tends to favor technical solutions (also mentioned by Hawken et al., 2021) over systemic, landscape-scale thinking.

Fig. 9 illustrates how Sponge City strategies–protect, delay, store, and release–are applied across site, neighborhood, and city scales. Delay and store, which address urban flooding and extreme rainfall, dominate at the site scale, reflecting a reliance on localized, small-scale interventions. In contrast, protect and release, essential for managing coastal flooding, river surges, and post-storm drainage, show minimal implementation, particularly at the city scale where they are most impactful. This shows a disconnect between the multi-scalar, systemic vision of Sponge City theory and its fragmented, practice-limited reality. This gap is compounded by land constraints common to many high-density urban areas. Maximizing buildable land often takes priority, limiting space for expansive protective or drainage systems (also mentioned by Li et al., 2017) and intensifying the tendency to implement only smaller-scale measures.

These patterns form a comparative baseline. Phase II turns to the Dutch lowlands as a critical test case to examine whether these tendencies persist under distinctive geomorphological conditions and governance traditions, or whether alternative configurations emerge–particularly in relation to hybrid green–blue measures, cross-scalar coherence, and the social embeddedness of implementation.

4.2. Phase II: mapping typologies: situating Sponge City projects in the Dutch lowlands

Building on the global typology established in Phase I, this section turns to the Dutch lowlands to examine how Sponge City strategies are assembled under distinctive lowland landscape conditions. Using eight documented projects, it tests where the global patterns–scale preferences, Delay/Store dominance, and variable social embeddedness–hold, and where the typology needs refinement. The typological matrix reads each case through landscape setting, urban context, scale, design rationale, infrastructural composition, and social embeddedness. In doing so, it moves from global pattern recognition to landscape-conditioned interpretation.

Sponge City interventions in the Netherlands are situated–both geographically and conceptually–within layered landscapes and lived urban realities. To trace their contours, this typological matrix maps eight documented urban Sponge City projects, examining their landscape settings, urban context, scale, design rationale, infrastructural composition, and degrees of social embeddedness. It moves beyond technical classifications, offering a lens through which to read spatial form, ecological responsiveness, and the societal undercurrents of climate-adaptive design.

These interventions are distributed across three dominant lowland landscape types: sand-ridge terrains (Nieuw-Binckhorst), riverine landscapes (Zomerhofkwartier, Benthemplein, Regenboog), and marine clay polders (Tidal Park, Zuiderpark, Waterlandkwartier, Smart Blue-Green Roofs). Each typology brings its own hydrological narrative. River landscapes, defined by dynamic flow and seasonal variability, often call for rapid drainage and retention systems–prompting blue-centric infrastructures. Polder landscapes, by contrast, demand sustained storage, ecological rehabilitation, and long-term adaptability. Here, landscape is not a backdrop but a formative agent shaping the logic of intervention (Table 1).

Projects are located primarily in deltaic cities (notably Rotterdam) and coastal urbanities (such as Den Haag), each contending with distinct pressures. In deltaic zones, strategies blend engineering and ecology, reflecting the push and pull of urban densification and water risk. Coastal settings, more residential in scale, gravitate toward neighborhood-based interventions attuned to finer spatial and social fabrics.

Scale emerges as a second axis. Five cases–Nieuw-Binckhorst, Zomerhofkwartier, Zuiderpark, Smart Blue-Green Roofs, and Regenboog–operate at the neighborhood level, embedding sponge logic within broader urban morphologies. Others, like Benthemplein, Tidal Park, and Waterlandkwartier, are site-specific: emblematic, experimental, and often detached from systemic planning. These microcosms serve as pilot sites—valuable, but insufficient on their own to reconfigure urban water resilience.

Design strategies vary along a spectrum of intent. Some projects (Zomerhofkwartier, Nieuw-Binckhorst, Regenboog, Smart Blue-Green Roofs) employ the full triad of Protect, Restore, Create. Others (Benthemplein, Waterlandkwartier) remain focused on restoration or retrofitting–limited in scope, yet reflective of a specific temporal moment. Tidal Park occupies a liminal space: a gesture of creation and renewal, yet lacking flood protection—an ecological offering without defensive depth.

Infrastructural compositions mirror these design logics. Hybrid blue-green systems are exemplified in Zomerhofkwartier and Smart Blue-Green Roofs, where infiltration zones, green roofs, and community gardens coexist with stormwater infrastructure. Benthemplein, in contrast, is a paradigm of engineered clarity: blue-dominant, controlled,

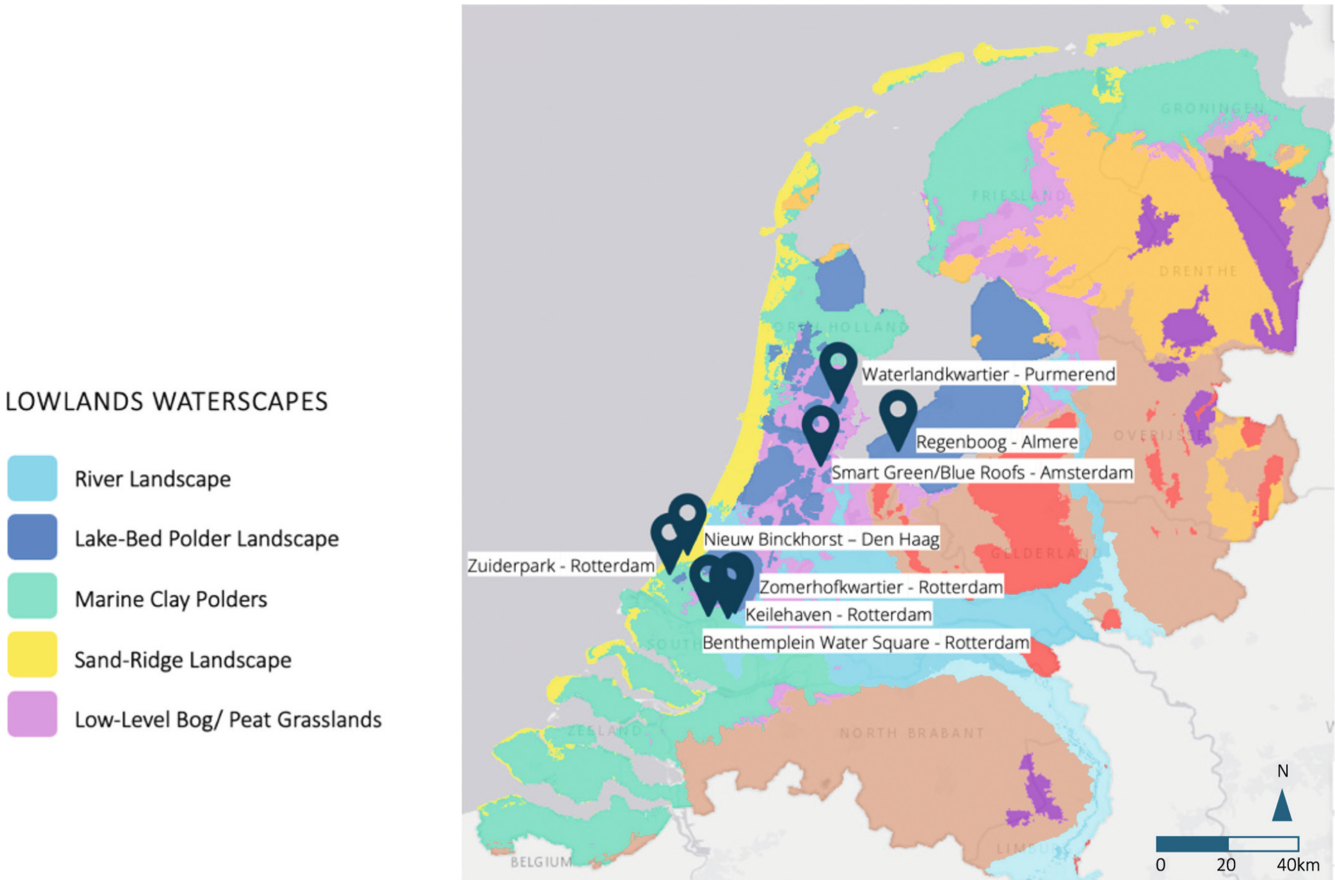


Fig. 10. Dutch lowlands types: Key regions include river areas, peat lowlands, and marine polders–each shaping Sponge City potential Data source: https://storymaps.arcgis.com/stories/ba85aa49141040bda0d088da11cf518e, 2020).

and visually iconic, yet socially distant. Others, such as Zuiderpark and Tidal Park, lean heavily on green infrastructure, celebrating ecological presence while remaining infrastructurally understated (Fig. 10).

4.2.1. How landscape in lowlands shapes urban sponge strategy

The spatial distribution of Sponge City interventions across the Dutch lowlands shows a critical interplay between landscape typologies and water resilience strategies. This analysis of eight cases–situated in marine clay polders, sand ridges, and deltaic river cities—examines

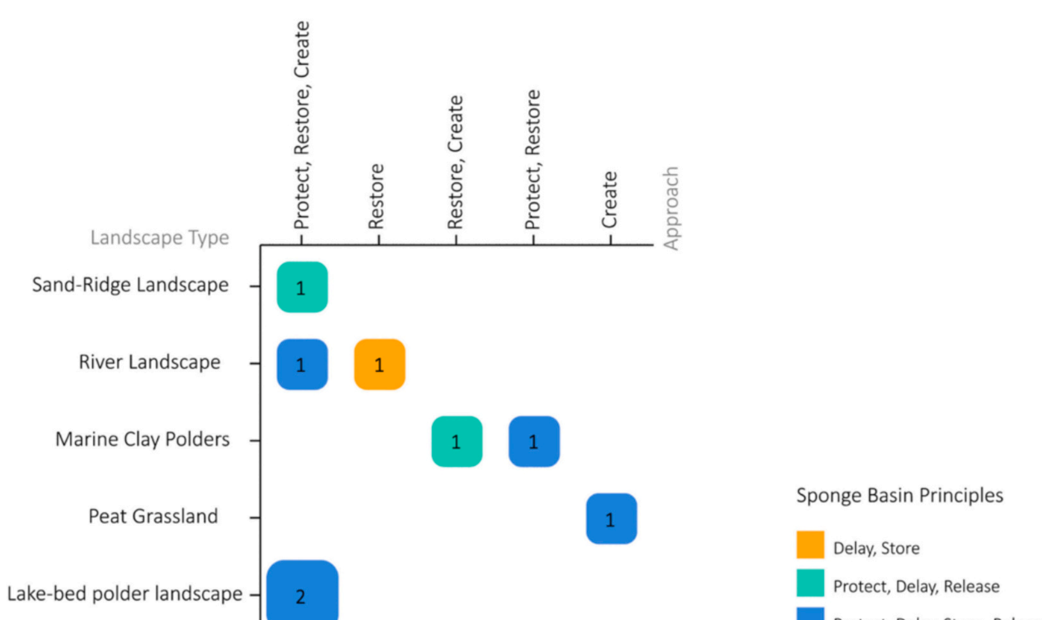


Fig. 11. Application of sponge basin principles across varying landscapes.

design logic, landscape integration, human-centricity, and multi-functionality to identify recurring patterns and gaps in adaptive urbanism.

Most cases are in Rotterdam and Den Haag, each facing distinct hydrological challenges. Rotterdam's deltaic terrain, in three cases, navigates complex flood risks, while Den Haag addresses coastal surges and groundwater rise. These conditions shape differentiated design responses.

Projects largely follow the Protect–Restore–Create model. Nieuw-Binckhorst and Zomerhofkwartier exemplify this triad through barriers, vegetative restoration, and infiltration. In contrast, Benthemplein focuses solely on engineered runoff mitigation, lacking green infrastructure and long-term ecological integration.

Hybrid strategies emerge in Tidal Park and Zuiderpark, merging water management (Delay, Store, Infiltrate) with public use like walkways and communal spaces. While Zomerhofkwartier demonstrates a comprehensive approach, others skew toward Delay, limiting systemic resilience.

Zomerhofkwartier and Zuiderpark embed multifunctional blue-green infrastructure–native planting, infiltration fields, water buffers–enhancing biodiversity, microclimates, and social well-being. Benthemplein, reliant on hardscape, illustrates the limitations of mono-functional design, underscoring the need for more integrated hybrids.

4.2.2. Landscape type vs sponge basin principles & approach

Fig. 11 conceptually maps sponge principles–Protect, Delay, Store, Release–across lowland landscape types. The project-level Approach (Protect/Restore/Create) is conceptually distinct from the Sponge Basin Principles (Protect/Delay/Store/Release) and from the operational water management strategies; this distinction is clarified in Supplementary 1.

Across the cases, Lake-bed polders show the most holistic alignment, supporting all four principles. River landscapes, despite high flood risk, emphasize only Delay and Store, reflecting a short-term focus over long-term resilience. Sand ridges, while aligned with Protect–Restore–Create, lack strong retention strategies—an oversight given their groundwater recharge potential.

Comparative evaluation shows mismatches between conceptual principles and applied strategies. At Nieuw-Binckhorst (sand ridge), infiltration and purification are implemented yet Protect and Release remain unaddressed. Similarly, in marine clay polders (Tidal Park and Zuiderpark), Release is not operationalized, despite its inclusion in planning. These gaps point to a disconnect between theory and practice, emphasizing the need for strategic alignment to realize multifunctional, resilient Sponge City systems.

4.2.3. Landscape type vs type of city & water strategies

This diagram visually illustrates the intersection of water management strategies with both landscape and urban typologies. Sand-Ridge Landscapes, associated with Coastal cities, heavily utilize Infiltration and Purification, aligning with the nature of permeable sandy soils and aquifer recharge needs. Conversely, Marine Clay Polders and Lake-bed Polders, typically in Delta/River contexts, tend to adopt broader, multifaceted strategies like Retention, Storage, and Purification, which suits their low-lying, flood-prone environments. However, the relatively small number of data entries may cause the visualization to under-represent intra-landscape diversity; especially for Peat Grasslands, which appear to only engage a narrow range of strategies.

In assessing the integration of water management strategies and Sponge Basin principles across Dutch landscapes, several critical gaps emerge that highlight inconsistencies in implementation. Sand-Ridge Landscapes, like Nieuw-Binckhorst, exhibit a narrow reliance on infiltration and purification techniques while omitting essential components like storage, drainage, and retention–mechanisms vital for buffering peak flows and enhancing adaptive capacity. Similarly, projects situated within River Landscapes, such as Benthemplein, neglect core strategies like purification and retention, suggesting a potential vulnerability in both water quality management and flood duration response.

Marine Clay Polders, particularly in low-lying urbanized areas like Tidal Park Keilehaven, show a notable absence of storage and drainage components despite their susceptibility to prolonged inundation. Furthermore, a mismatch between applied strategies and guiding Sponge Basin principles is evident: projects like Nieuw-Binckhorst and Tidal Park Keilehaven fail to operationalize the Store principle, while Benthemplein omits Protect and Release—key elements for ecological safeguarding and hydrological flexibility. These inconsistencies highlight the need for more holistic, landscape-specific application of Sponge City principles to ensure systemic resilience in the face of intensifying climatic pressures.

The alignment between landscape-specific hydrological risks and the implemented water strategies shows a critical oversight in at least one key urban intervention. In the case of the Benthemplein Water Square, located within a River Landscape, the expected risks include flooding and fluvial overflow. While the project applies strategies such as infiltration, storage, and drainage, which collectively address issues like surface runoff and waterlogging, it fails to engage strategies like retention, which are specifically suited to managing fluvial overflow–a core vulnerability in riverine contexts. This mismatch exposes a potential shortfall in system responsiveness during peak river discharge events, thereby undermining the resilience objective of Sponge City interventions. The finding highlights the importance of risk-informed planning approach, where strategy deployment is directly traceable to the dominant hydrological threats within each landscape typology.

4.2.4. Distribution of Green, Blue, and Green-Blue strategies: a cross-case pattern

To further unpack how Sponge City principles materialized in practice, a code-document analysis was conducted using ATLAS.ti across eight Dutch projects (Fig. 13a & b).

The resulting Sankey diagram (Fig. 14), and distribution table Y offer a more granular understanding of design strategies embedded in the visual and spatial fabric of these interventions. What emerges is a clear imbalance: green strategies dominate, blue strategies are present but often singular in purpose, while green-blue hybrids—despite being the most aligned with the systemic ambition of Sponge Cities—remain underrepresented.

This distribution highlights not only the fragmented application of sponge logic, but also the persistence of functionally siloed interventions. Projects such as Zomerhofkwartier and Keilehaven come closest to a layered integration, where hydrological, ecological, and social functions coalesce. Others, such as Benthemplein, while technically effective, remain aesthetic and hydrologically expressive, yet socially and ecologically thin—a spectacle of infrastructure rather than a lived, adaptive system.

Importantly, many of these strategies were not explicitly mentioned in project documentation or public-facing materials. Rather, they became legible through the visual grammar of plans, sections, and renderings–coded elements such as bioswales, infiltration zones, or blue-green rooftops that silently perform but remain unnamed. This lack of visibility, both literal and conceptual, limits their pedagogical and participatory potential. Making these strategies more explicit–not only through design but through language–can support broader climate awareness and empower residents to recognize, value, and engage with the adaptive capacities of their environments.

Design, in this context, becomes not only a means of intervention, but of translation–between climate processes and urban life, between the logic of water and the everyday. When strategies remain buried in drawings or implicit in form, their relational and educational capacity is lost. By naming and narrating these spatial logics, Sponge Cities can become more than technical systems–they can become shared imaginaries of resilience, where form, function, and meaning are intertwined.

4.2.5. Spatial justice in Sponge Cities

While the hydrological and ecological effectiveness of Sponge City projects has been explored, their social inclusivity–particularly for vulnerable groups like the elderly–remains underexamined. This section evaluates five Dutch interventions through social inclusion, elderly accessibility, and recreational multifunctionality, showing how adaptive infrastructure can support socially just urbanism.

All five projects integrate public space as parks, squares, or green corridors. However, participatory planning varies: Nieuw-Binckhorst and Benthemplein provide communal space without evidence of stakeholder engagement, while Zomerhofkwartier and Zuiderpark involve residents and community organizations. Zuiderpark's structured collaboration stands out as democratic spatial production.

Social inclusion is visible through green spaces and educational efforts, but only Zomerhofkwartier and Zuiderpark embed community roles in both design and governance. Still, accessibility for the elderly is inconsistent–despite barrier-free entries, features like rest spots, tactile paths, and railings remain insufficient. Benthemplein's stairs and limited seating highlights gaps between design intention and inclusive execution.

Recreational value appears across projects–via paths, seating, and sports–but varies in scope. Zomerhofkwartier and Zuiderpark exemplify inclusive programming like urban farming, education and play—appealing to diverse users. Benthemplein focuses narrowly on youth sports, limiting intergenerational and sensory dimensions. Tidal Park, while ecologically rich, lacks active programming, missing chances to connect people with its tidal landscape.

This evaluation highlights the need for Sponge City strategies to move beyond hydrology and engage with universal design, participatory governance, and equitable access. We recommend: (a) institutionalizing co-creation processes from the earliest stages of planning, (b) embedding universal design features (such as railings, rest points, and sensory elements) throughout, (c) ensuring inclusive recreational programming for diverse ages and needs, and (d) applying measurable indicators to monitor both accessibility and social outcomes.

4.2.6. Performance modeling potential of Dutch Sponge Cities (see App. 1, Fig. 15)

As Sponge Cities are conceptualized to manage, store, and reuse urban water through ecologically sensitive infrastructure, their potential effectiveness hinges on how well they perform key hydrological, ecological, and climatic functions. This section provides a qualitative assessment of performance modeling potential for eight Dutch Sponge City interventions, based on their documented use of green and blue infrastructure. While direct quantitative data (e.g., water retention volumes, biodiversity metrics, cooling rates) is not available, the descriptive design strategies offer substantial insight into each project's likely performance in stormwater control, biodiversity enhancement, microclimate regulation, and ecosystem connectivity.

Hydrological Capacity & Water Retention: Projects like Zomerhofkwartier and Smart Blue-Green Roofs demonstrate strong retention potential via layered systems (e.g., blue roofs, infiltration zones). Participatory awareness around runoff areas suggests design intentions for user education and behavior change, further enhancing hydrological performance. Benthemplein excels in engineered storage but lacks greenery. Vegetated sites like Tidal Park and Zuiderpark focus more on slow infiltration than immediate runoff control, while others show partial or unclear hydrological strategies.

Biodiversity Enhancement & Habitat Regeneration: Projects using native species, softened quays, nature-friendly shorelines, and wetland vegetation present clear ecological value. Zuiderpark, Zomerhofkwartier, and Tidal Park emphasize native vegetation, green corridors, and pocket ecologies. Their layered plant palettes–from drought-resistant grasses to amphibious shrubs–support pollinators, local fauna, and climate resilience. Tidal Park Keilehaven, in particular, transforms a post-industrial waterfront into a tidal ecological buffer, benefiting both aquatic and terrestrial ecosystems and enhancing habitat regeneration and connectivity.

Urban Cooling & Microclimate Regulation: Vegetative canopies contribute to cooling via shade, evapotranspiration, and albedo modification. Benthemplein includes cooling fountains and water-integrated seating, though its paved surfaces may limit long-term thermal regulation. In contrast, Zomerhofkwartier, Zuiderpark, and Smart Blue-Green Roofs provide broader green coverage, suggesting stronger potential to reduce urban heat islands. Waterlandkwartier and Regenboog include infiltration fields and shaded paths, though further detail is needed to assess thermal impact. The absence of comprehensive blue-green synergy in some projects, such as Nieuw-Binckhorst, may limit cooling effects despite vegetation.

Ecosystem Services & Educational Impact: Projects that engage the public with visible ecological processes offer co-benefits beyond infrastructure. Zomerhofkwartier stands out by combining blue infrastructure with community education on runoff. Regenboog and Zuiderpark also reference educational programming and public awareness, linking design to environmental stewardship and fostering adaptive behavior. In contrast, Benthemplein and Tidal Park, while strong in hydrological or ecological terms, lack participatory and educational components, limiting their broader impact.

In the absence of empirical measurements, a qualitative reading of these projects still shows clear differences in their potential. Zomerhofkwartier, Smart Blue-Green Roofs, and Zuiderpark stand out for integrated design, addressing not just water management but also ecology, microclimate, and public engagement. Benthemplein impresses in hydrological engineering but falls short on ecological integration. Meanwhile, Tidal Park contributes ecological value but has limited stormwater management capacity.

To better understand how these interventions truly perform, future evaluations will need to go beyond design descriptions. Empirical data–on retention, biodiversity, and user experience–will be important. Tools like SWMM and ENVI-met can help translate these concepts into evidence-based strategies.

Taken together, this typological mapping reveals the heterogeneity of Sponge City practice in the Dutch lowlands. While all projects respond to water stress, only a fewlike Zomerhofkwartier and Smart Blue-Green Roofs–successfully integrate landscape logic, technical innovation, and social imagination. These models point forward: not as templates to replicate, but as invitations to reimagine Sponge City design as a layered, inclusive, and context-sensitive practice. In a future of rising waters, resilience must be more than engineered–it must be lived.

Despite growing attention to climate resilience, many initiatives remain narrowly focused on technical and ecological aspects, often overlooking the social fabric of urban environments. This lack of a social dimension risks creating interventions that are efficient in water management but disconnected from the lived realities of local communities. Without integrating social equity, cultural diversity, and participatory governance, Sponge City designs risk reinforcing inequalities and overlooking marginalized communities. To reach their full potential, they must be seen not just as hydrological systems, but as inclusive urban spaces where all residents can engage, thrive, and share ownership.

Typological distinctions across landscape types highlight the need for more holistic approaches. River landscapes, especially in Rotterdam, deploy hybrid systems like water squares and blue-green corridors, addressing both acute flooding and systemic water challenges. Marine clay polders emphasize ecological buffers to mediate tidal pressures, while sand-ridge sites in Den Haag prioritize greening but often lack water storage—potentially overlooking heat resilience.

A comparative reading of sponge basin principles (protect, delay, store, release) highlights these contrasts: river landscapes apply all four, marine polders focus on buffering, and sand-ridge sites often omit storage. These patterns call for a more codified, landscape-sensitive planning framework that aligns hydrological strategies with local morphology and social equity. If Sponge Cities are to transcend their role as infrastructural solutions and become truly transformative, they need to be situated at the intersection of ecology, technology, and lived experience. Only then can they improve urban environments that are not only climate-adaptive but also inclusive, equitable, and deeply rooted in place.

4.2.7. Discussion with existing literature

This paper frames Sponge Cities as socio-ecological systems unfolding through infrastructure, landscape, temporality, and lived experience. This place-based reading in the Dutch lowlands sits somewhat apart from the dominant orientation of the previous literature. Conceptual contributions such as Chan et al. (2018), He et al. (2019), and McBride (2023) do expand Sponge Cities beyond drainage, but mostly at the level of policy paradigms, co-benefits, and national narratives, with temporality and everyday experience remaining marginal.

By contrast, technical and modeling studies such as Avashia and Garg (2020); Liu et al. (2025); Tan et al. (2024); Zhai et al. (2021); Xu et al. (2024); and Li et al. (2026b) treat "place" primarily as hydrologic or spatial structure rather than as an experiential condition. Review and meta-analyses as Stijnen et al. (2024); Chikhi et al. (2023); and Sobhaninia et al. (2025). begin to hint at socio-ecological trade-offs and siting politics. However, largely from a higher level of abstraction. Against this backdrop, the contribution here lies in advancing a situated, landscape-typology-based interpretation of sponge principles in a European delta context, making temporality and lived urban life explicit analytical categories rather than implicit assumptions.

This paper argues the "lack of social dimension" sits on firm ground, but it also clearly pushes beyond it in scope and political sharpness. The critique of late-stage or limited participation aligns with survey evidence showing uneven awareness between sponge and non-sponge districts and support that is conditional on trust, knowledge, and perceived efficacy (Luo et al., 2022; Shi et al., 2024). It also resonates with findings that willingness to contribute to maintenance is real but fragile, and stratified by age and socio-economic position (Ding et al. (2019); Qiao & Randrup, 2022). Where these studies mostly remain at the level of attitudes and financing preferences, this paper extends the implications into the structural question of who benefits, who pays, and who is prioritized in the spatial politics of adaptation.

Comparative and institutional studies stress that China's rapid implementation comes with participation deficits and long-term stewardship ambiguities, while other contexts struggle with slower, fragmented coordination (L. Li et al., 2020). The emphasis placed on mistrust and missing co-production is reinforced by work on the fragility of ad-hoc collaborations (Malekpour et al. (2021) and the role of tacit professional and administrative cultures in obstructing implementation (Yao & Bell, 2022).

Even outside the Chinese context, expert-based assessments underline that governance capacity and state backing remain decisive constraints (Lubaina et al., 2025). These arguments are woven into an integrated claim: infrastructure cannot be treated as a proxy for resilience in the absence of procedural legitimacy and local agency.

A distinct advance is the explicit environmental justice and vulnerability lens. Much of the literature only partially gestures toward equity through demographic differences in willingness to pay, or through generalized trade-off frameworks (Chikhi et al., 2023; Ding et al., 2019; Qiao & Randrup, 2022; Stijnen et al., 2024). By foregrounding green gentrification, displacement risk, and the need for anti-displacement safeguards (e.g., Anguelovski et al., 2022; Jiang et al., 2018; Lu et al., 2025; Sánchez et al., 2026), this study moves from distributive observations to a stronger recognition and procedural critique. This reframes Sponge Cities as a contested socio-ecological project in which social networks, local knowledge, and community resilience function as essential infrastructure rather than secondary co-benefits.

The discussion of the "scale paradox" here, sits within the technical multi-scalar literature while repositioning it in a more political and experiential register. Multi-scale performance studies demonstrate that coordination across nested hydrological units improves outcomes, supporting the insistence that integration matters (Zhai et al., 2021).

Likewise, enhanced planning frameworks that combine Dutch water principles with plot–block–district–watershed structuring lend methodological backing to the cross-scale critique (Chen et al., 2021). City- and district-level zoning and modeling work mirrors the observation that implementation gravitates toward larger, more legible and indicator-friendly interventions (Deng et al., 2022; Liu et al., 2025; Tan et al., 2024). Even outside the Chinese context, retrofit evidence confirms that urban form and the scale of intervention condition feasibility, reinforcing the point that design ideals are filtered through morphological realities (Haase, 2025).

The extension here lies in treating scale not only as a hydrological hierarchy but as a political economy of implementation. While the literature acknowledges scale largely as a planning or modeling unit, the argument asks why certain scales become institutionally attractive (fundable, visible, easy to govern) while building- and buffer-level measures remain aspirational. This marks a shift from the largely technocratic framing by Zhai et al. (2021), Chen et al. (2021), Liu et al. (2025), Tan et al. (2024), Deng et al. (2022), and Haase (2025).

The discussion further adds a social-experiential reading of scale, highlighting what is lost when smaller, socially embedded interventions are marginalized–everyday agency, neighborhood stewardship, and incremental, place-specific adaptations that often make resilience durable.

In this sense, the critique converges with broader concerns about siloed and single function siting, yet pushes the question from analytical inconsistency toward implementation politics. Scale, then, is not only a technical choice about performance efficiency but a governance decision that shapes whose practices, capacities, and daily landscapes are allowed to count as resilience.

The global mapping of Green/Blue/Green–Blue strategies (Fig. 6), hydrological processes (Fig. 7), and the Protect–Delay–Store–Release lens (Figs. 8–9) places this study within international debates on typologies, biases, and silences of sponge implementation. The closest resonance is with Sobhaninia et al. (2025), whose global review identifies recurring preferences for a familiar toolkit and persistent functional silos between stormwater and heat, alongside weak justice-oriented siting.

The imbalance of Delay and Store dominating while Protect and Release remain marginal in some cases also aligns with Chikhi et al.'s (2023) critique of over-reliance on infiltration-driven measures and insufficient watershed integration in Chinese practice. Meanwhile, facility performance and climate-sensitive payback (Xu et al., 2024; Li et al., 2026a) strengthens the distinction between widely portable core measures and more context-dependent innovations, even if these studies do not articulate the sponge principles vocabulary directly.

What is added here is a normative, systemic lens that the field largely lacks. The cross-country reading moves beyond narratives of Chinese leadership by comparing planning and strategy repertoires across the Netherlands, China, Australia, France, and India, treating global diffusion not as a neutral transfer of best practice but as a selective translation shaped by governance, landscape, and institutional habit.

Beyond Haase's (2025) European case in Leipzig (largely framed through technical feasibility) and Chen et al.'s (2021) use of Dutch principles in a Chinese planning context, the literature offers limited engagement with Western European lowland conditions. The absence of European deltaic typologies across a large body of recent work (e.g., Chikhi et al. (2023); L. N. Li et al. (2024); Jiang et al. (2022); Malekpour et al. (2021); Shi et al. (2024); Yao and Bell (2022); Lubaina et al. (2025); Luo et al. (2022); McBride (2023); Li et al. (2026b); Stijnen et al. (2024); Xu et al. (2024); Liu et al. (2025); Sobhaninia et al. (2025); Qiao and Randrup (2022)) makes the Dutch lowlands not a minor extension, but a substantive geographic and conceptual gap addressed here.

What is distinct here, is not only the choice of cases but the analytical

Table 2
The distribution of Sponge City strategies across cases from the code-document analysis. Rows with solid outline show total sponge city strategies, while dashed outlines highlight the top six coded strategies.

		2 Benthemplein... 17	4 Nieuw Binckho... 5	5 Zomerhofkwar... 6	6 Keilehaven Rot... 8	7 Zuiderpark De... 5	8 Smart Blue Gr... 5	9 Regenboog Al... 5	10 Waterlandkw... 14	Totals
Blue strategy	60	4	2		2	3	1	2	4	18
Blue strategy: biological retention	16				1	1			2	4
Blue strategy: buried storage	7						1			1
Blue strategy: floodplain	3		2		1					3
Blue strategy: harvesting system	10							1		1
Blue strategy: open storage	10	3				1		1		5
Blue strategy: water elements	9	1				1			2	4
Green strategy	77	1	1	4	4	1	2	2	5	20
Green strategy: facade garden	11								1	1
Green strategy: green roof	7			1					1	2
Green strategy: green wall	4			1					1	2
Green strategy: helophyte filter	8				1		1			2
Green strategy: permeable pavement	14			1				1	1	3
Green strategy: shade	24	1	1	1	2	1	1	1	1	9
Green strategy: softening	9				1					1
Green/blue strategy	57	5	2	2	1		1			11
Green/blue strategy: bluegreen roof	1						1			1
Green/blue strategy: raingarden	19	4		1						5
Green/blue strategy: urban forest	13		2	1	1					4
Green/blue strategy: water square	5	1								1
Totals		20	10	12	14	8	8	8	18	98

grammar. By treating landscape types (sand ridge, river landscape, marine clay polder, peat grassland, and lake-bed polders) as structuring conditions for sponge logic, the analysis frames geomorphology and hydrological history as co-producers of design feasibility and institutional prioritization.

While multi-scale work such as Zhai et al. (2021) points to catchment-level integration, it does not operationalize landscape typologies in this way. The study further advances the field by reading landscape type, city type (coastal, delta, river), and scale (site, neighborhood, city) as interacting axes, and then overlaying these with Sponge Basin Principles and water strategies. This intersectional mapping (landscape × city type × scale × strategy) does not appear in the large body of previous studies.

The mismatches in Sponge Basin Principles translate the often-generalized "theory–practice gap" into landscape-specific evidence. This reframes Sponge City implementation as a context-sensitive negotiation rather than a transferable checklist and shows that resilience outcomes in lowland Europe hinge on whether sponge principles align with the logics of place, not merely with the visibility of blue–green form.

The qualitative performance reading also complements a literature dominated by modeling, zoning, and life-cycle calculations. The hydrological emphasis of Tan et al. (2024), Zhai et al., 2021), and Deng et al. (2022), and the facility-level environmental accounting in Xu et al. (2024) and Li et al. (2026a), show what measures can do under specified assumptions; the analysis here asks what these measures become when assembled as public landscapes with uneven social embeddedness.

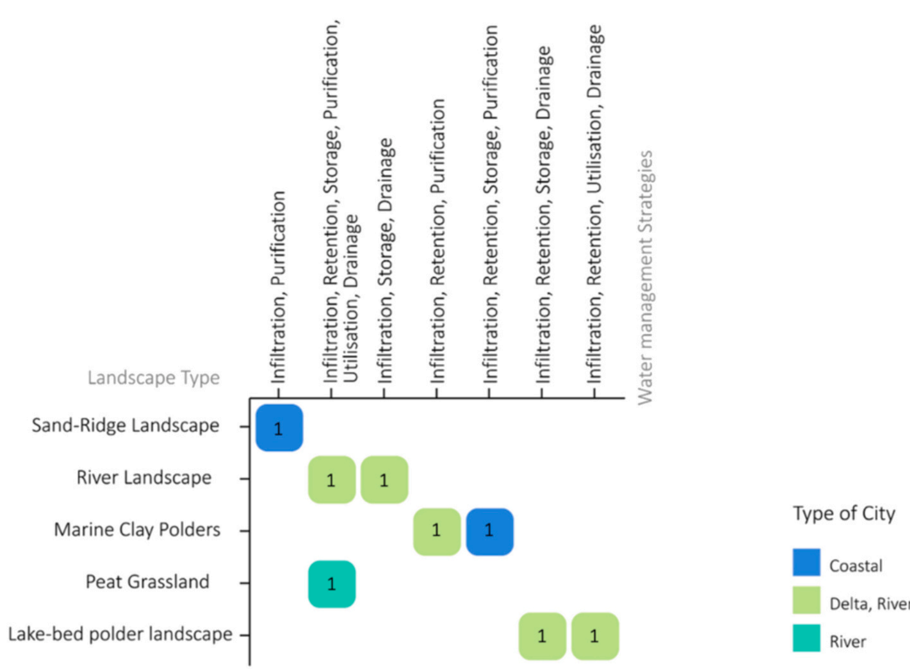
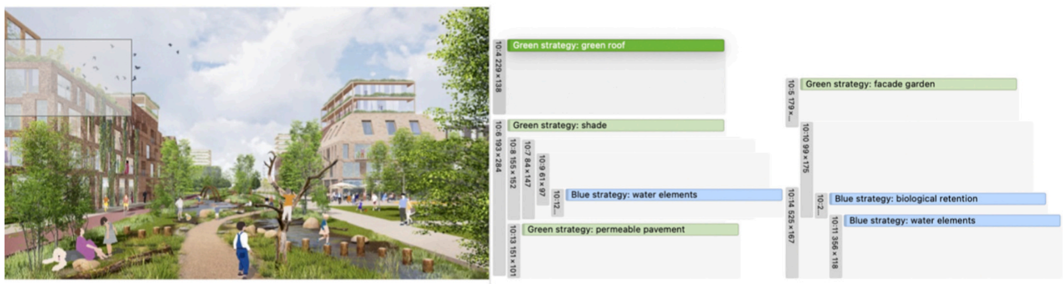


Fig. 12. Maps landscape types against water management strategies, segmented by city typology (Coastal, Delta-River, River).

a) Coded figure exemplar in ATLAS.ti for Zomerhofkwartier in Rotterdam



b) Coded figure exemplar in ATLAS.ti for Waterlandkwartier in Purmerend

Fig. 13. (a) Coded figure exemplar in ATLAS.ti for Zomerhofkwartier in Rotterdam. (b) Coded figure exemplar in ATLAS.ti for Waterlandkwartier in Purmerend.

The result is a sharper differentiation between projects that are technically legible yet socially and ecologically thin (Benthemplein), ecologically promising but limited in flood-protective depth (Tidal Park), and those that more convincingly stitch hydrology, ecology, and everyday use into a lived resilience repertoire (Zomerhofkwartier, Smart Blue-Green Roofs, Zuiderpark). This kind of situated judgement is precisely what the review literature calls for but rarely demonstrates with European empirical detail (Chikhi et al., 2023).

Equally important is the insistence that education and public engagement are not peripheral outcomes but designed capacities. Where survey-based studies register awareness and knowledge as explanatory variables (Ding et al., 2019; Luo et al., 2022; Shi et al., 2024), this study highlight how awareness can be spatialized through visible runoff narratives, legible blue–green cues, and stewardship-oriented programming.

In this way, Chan et al. (2018), He et al. (2019), and McBride (2023) are aligned with the argument that Sponge City is more than drainage, but the emphasis is relocated from national narratives and policy paradigms to the grounded terrains of landscape typology, temporality, and lived urban practice.

4.2.8. Practical implications: actionable recommendations for policy and design

The typological and cross-scalar patterns identified in the Dutch lowlands point to several concrete directions for practice. Rather than adding more isolated pilots, it calls municipalities and design teams to rethink how Sponge City strategies are conceived, situated, and governed.

(1) Landscape-Sensitive Planning Frameworks: The findings highlight the need for planning frameworks that foreground landscape logic rather than retrofitting measures onto sites. The analysis shows that sand-ridge environments, for instance, tend to underemphasize storage and retention despite their potential for groundwater recharge, while river and marine clay polder landscapes often neglect protect–release functions that are crucial for managing fluvial and tidal dynamics (also based on Table 2 and Figs. 11–12). Embedding landscape–strategy matrices in design briefs, zoning tools, and environmental assessments can help ensure that interventions respond to the hydrological logics and risks of specific lowland types.
(2) Multi-Scalar Integration through Governance coherence: Dutch Sponge City projects would benefit from stronger multi-scalar integration. Many of the examined interventions perform well at the site or neighborhood scale, yet remain only loosely connected to district or watershed systems. Municipalities can address this by requiring that project proposals demonstrate how local measures contribute to broader hydrological and ecological networks.
(3) Embedding Social Inclusion through Universal Design Standards: The Dutch cases underline the importance of embedding universal design into blue–green infrastructure. To ensure equitable adaptation, Sponge City guidelines should incorporate universal design principles, such as barrier-free circulation, rest areas, shading, tactile surfaces, and age-inclusive amenities; especially in public-facing blue-green infrastructures. Co-creation protocols, specifying when and how communities (including elderly and vulnerable groups) are involved can sustain long-term adaptability within lived experience.

5. Conclusion

This study explores how Sponge City design unfolds between ecological ambition and social realities, revealing that resilient urban futures require not only hydrological adaptation but also context-sensitive strategies that engage landscapes, communities, and climatic processes as interdependent systems.

Through a layered, comparative analysis of global and Dutch cases, the research identifies a persistent gap between theoretical principles and practical implementation–particularly in the integration of social dimensions such as equity, participation, and community resilience. While many interventions demonstrate technical sophistication, they often lack meaningful public involvement and risk reinforcing socio-spatial inequalities.

The study's distinctive contribution lies in its cross-scalar, typologically informed methodology, moving beyond technical assessments to highlight how Sponge City strategies perform within specific ecological and social contexts. Dutch cases reveal both strengths and inconsistencies: while river landscapes implement all core principles

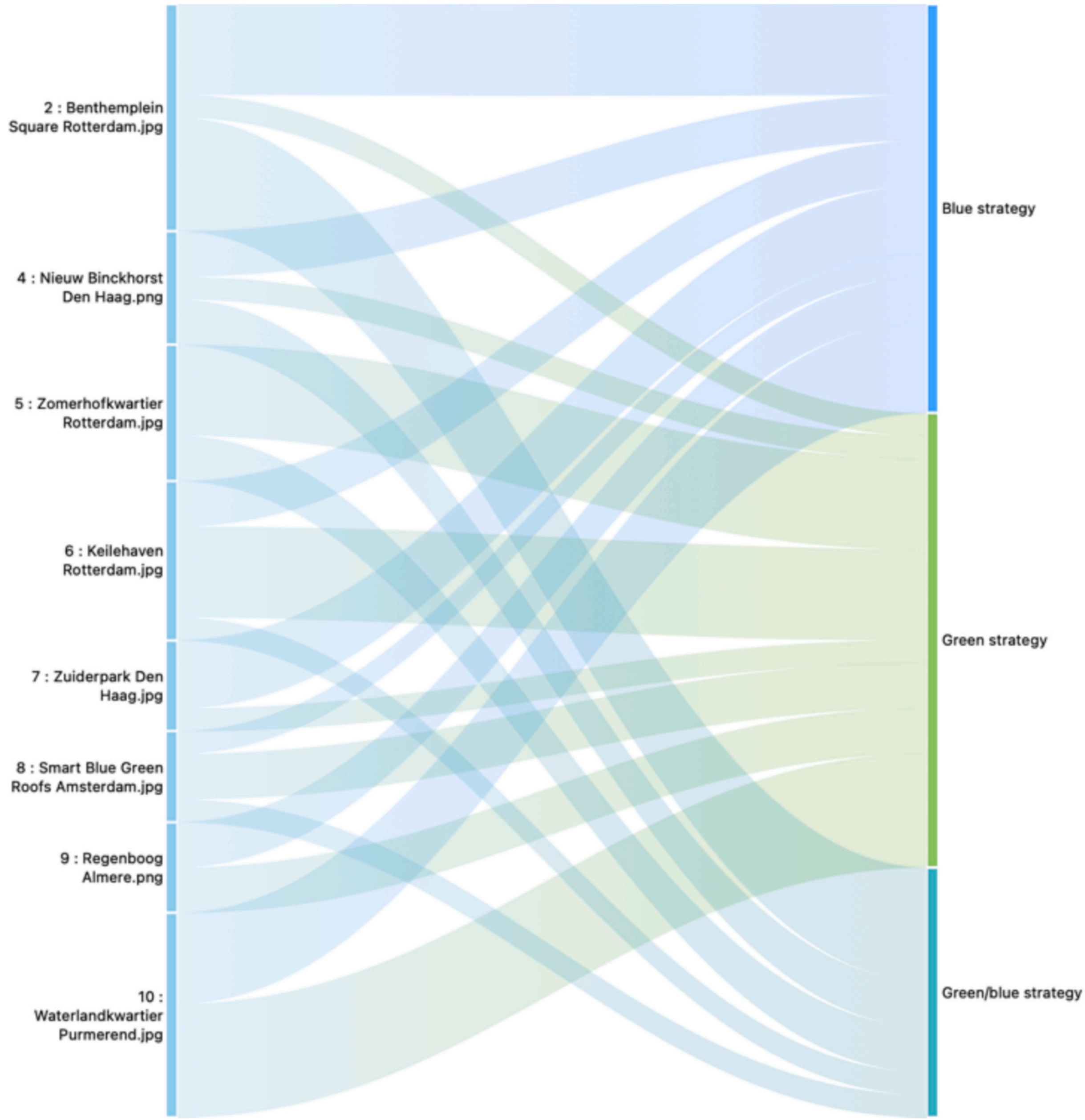


Fig. 14. Sankey diagram showing the distribution of Sponge City strategies across cases (code-document analysis, and *Classification of strategies as green, blue or green–blue follows the rule-based criteria described in the Methods*). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 15. Performance modeling potential of Dutch Sponge Cities.

(protect, delay, store, release), others–especially in sand-ridge or marine clay typologies–lack key water retention elements, signaling the need for more coherent, place-based planning.

Addressing these challenges requires reframing design as a socially embedded, participatory process. Recognizing design as an ongoing, collaborative engagement that actively incorporates diverse stakeholders throughout planning, execution, and maintenance stages is important. Sponge Cities must be understood not just as infrastructure, but as shared, adaptive urban landscapes.

The findings provide actionable knowledge for implementing Sponge City strategies in diverse landscapes. However, to deepen their applicability, future work should integrate quantitative assessments, experimental modeling, and longitudinal studies that capture both ecological and socio-cultural impacts. The cases discussed here could, for instance, be translated into SWMM- or ENVI-met-ready models, provided that harmonized datasets on catchment geometry, soils, storage volumes, control rules, microclimatic conditions, and vegetation structure are systematically collected across sites. Arguing for design as a 'socially significant activity' remains essential in this context, as this view responds to current gaps in how we understand the relationship between design, climate adaptation, and society.

Integrating these dual metrics–ecological and social–enables multidimensional evaluations, offering clearer guidance on the effectiveness and sustainability of their interventions. As Sponge City strategies are explored globally and within the Netherlands' five lowland water landscapes, it's crucial to recognize that design is always relational–-shaped by specific social, cultural, and ecological contexts. Simplistic definitions of "design" or "society" fall short. Instead, understanding how communities engage with their environments reveals the forces shaping Sponge City projects.

These findings also highlight that while Sponge City principles are increasingly present in Dutch urban design, their implementation remains fragmented, with hybrid strategies often under-articulated or visually embedded but not formally acknowledged. Many strategies identified through visual and spatial analysis were not explicitly mentioned in project reports or public documents, limiting broader public awareness. Strengthening the communicative dimension–by making design strategies more explicit and legible–could help foster climate literacy, empower citizen engagement, and align infrastructural adaptation with everyday urban experiences. Moving forward, policy frameworks must evolve beyond technical performance criteria to embed design literacy, participatory visibility, and multi-scalar integration, ensuring that Sponge Cities function not merely as infrastructures of resilience but as shared landscapes of adaptation.

This human-centered perspective ensures that design strategies are better aligned to local conditions and community needs. The next step could involve exploring spatial and temporal dynamics—studying how the core principles (protect, delay, store, release) interact across urban scales and adapt to climate variability.

It is important to acknowledge that this study is based on secondary data and published sources, which may not fully capture the lived experiences of users or the on-the-ground performance of interventions. While international strategies were not evaluated through direct fieldwork, and the Dutch cases remain context-specific, potentially limiting generalizability, the structured and comparative methodology still enables valuable insights into the technical rationale and social implications of Sponge City design. Future studies may benefit from integrating primary data, experimental modeling, or longitudinal analysis to strengthen the evidence base and enhance contextual relevance.

To move from experimentation to long-term transformation, Sponge City design need to be grounded in concrete, context-sensitive practices that link water, landscape, and everyday urban life. The analysis in this study points to four key directions: aligning strategies with landscape and risk; ensuring that site and neighborhood projects are connected to district and watershed planning; embedding universal design and participation so interventions support daily use and shared responsibility; and establishing monitoring systems that track hydrological, ecological, and social effects over time.

In this view, the success of Sponge City strategies depends not only on hydrological performance but also on relationships between people, institutions, and environments. When design is understandable to residents, when communities are involved in shaping and maintaining spaces, and when planning frameworks respect local conditions and lived experience, Sponge Cities can move beyond technical fixes and begin to function as shared, resilient urban grounds. Through such integration can Sponge Cities fulfil their potential as resilient landscapes-rooted not only in ecological function but also in the everyday spatial and social realities of urban life.

CRediT authorship contribution statement

Maryam Naghibi: Writing – original draft, Visualization, Supervision, Project administration, Methodology, Conceptualization. **Gillian Weber:** Writing – review & editing, Visualization, Methodology, Conceptualization. **Evgenia Vamvakousi:** Writing – review & editing, Visualization, Methodology, Conceptualization. **Claudiu Forgaci:** Writing – review & editing, Supervision.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT to check grammar, correct typos, and refine wording and sentence structure. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cities.2026.107320.

Data availability

Data will be made available on request.

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