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From Grey Gap to Ecological Resilience: Quantifying the Spatiotemporal Evolution of Hybrid Water Infrastructure in a Subtropical Megacity (1994–2024)

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Abstract

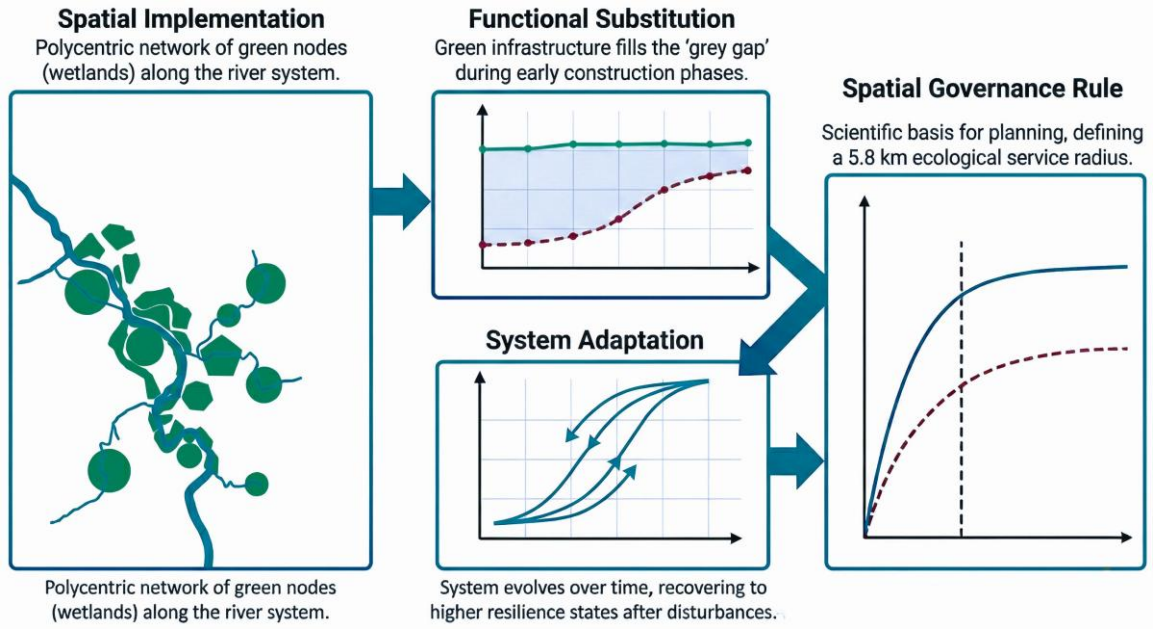
The growth of rapidly urbanizing Asian megacities routinely outpaces the construction of centralized sanitation, leaving a protracted interval in which environmental, public-health, and governance burdens accumulate. Drawing on three decades of evidence (1994–2024) from the Danshui River Basin, Taipei, this study interrogates how decentralized Green Infrastructure and centralized Grey Infrastructure jointly govern urban water quality. We integrate long-term water-quality monitoring, sewerage-connection records, and spatially explicit ecological indicators, and read their coupled performance through Ostrom's Theory of Polycentric Governance. Two regimes emerged. During a "gap-filling" phase (2004–2012), a network of 13 constructed wetlands lowered riparian ammonia-nitrogen (NH_3–N) from 5.0 to 1.3 $mg \cdot L^{-1}$ even as public sewerage connection in New Taipei City reached only about 33%. The Green subsystem discharged a service that the Grey subsystem could not yet provide. In the subsequent "maturation" phase (2013–2024), resilience, operationalized as the inverse coefficient of variation ($S = \mu/\sigma$), showed that the wetlands sustained high functional stability in pollutant removal despite contracting maintenance budgets and intensifying climatic disturbance. Spatial analysis using Local Indicators of Spatial Association and indicator kriging resolved a belt-like disturbance signature on avian biodiversity with an influence range of approximately 5.8 km. A cost comparison indicates that the decentralized Green subsystem delivered durable ecosystem services at roughly 10–15% of the corresponding Grey Infrastructure expenditure.

These multi-decadal results position Green–Grey coupling not as a stopgap but as a scalable, anticipatory governance pathway for urban water management across the rapidly urbanizing Global South.

Keywords: Nature-based Solutions (NbS); Green-Grey Coupling; Polycentric Governance; Urban Water Resilience; Spatial Statistics; Longitudinal Analysis

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Graphical Abstract



1. Introduction

1.1 The Urban Water Crisis and Infrastructure Lock-in

Megacities globally are confronting a fracturing hydro-social contract (i.e., the evolving set of institutional arrangements, infrastructures, and societal expectations that bind a community to its water systems; Linton and Budds 2014), where the reliance on traditional centralized wastewater treatment systems, often termed "Grey Infrastructure", is increasingly being viewed as capital-intensive, rigid, and slow to deploy (Larsen et al. 2016; Wong and Brown 2009). While these centralized systems remain effective for managing point-source pollution, they frequently fail to mitigate the amount of non-point source runoff (rain and snow) and lack the adaptive capacity required to withstand intensifying climate extremes (Oral et al. 2020). Our ability to understand ecological processes, some that have been occurring naturally for billions of years has improved substantially in the last few decades. Consequently, the integration of what we now call Nature-based Solutions (NbS), or Green Infrastructure, into the management and stewardship of our natural resources has emerged as a critical shift toward resilient urban water management and achieving co-benefits for biodiversity and human well-being (Frantzeskaki 2019; Kabisch et al. 2017). Cities and society that are aiming to become sustainable are discussing and integrating NbS and Blue–Green Infrastructure strategies into their urban adaptation vision (Nakai et al. 2025). As noted by Hunter (1998), the short- and long-term vision of urban sustainability must move away from the engineering-fix approaches for water management to solutions that maintain the functional integrity of ecosystems and capitalize on naturally occurring processes. Here, “Grey Infrastructure” denotes the engineered, built assets (sewers, pumping stations, and centralized treatment plants) and

should not be confused with “greywater,” the wastewater from sinks, showers, and laundry; the wetlands in this study treat greywater and municipal sewage. Such systems where the greywater is not source-separated and included in the sewage stream are called combined sewer systems. In this context, point-source pollution refers to discrete, pipe-end discharges, whereas non-point (diffuse) pollution is mobilized from many dispersed locations by rainfall and snowmelt and arrives as both a hydraulic (storm-volume) load and a diffuse pollutant load. Compounding these limitations, much of the Grey Infrastructure legacy was dimensioned for populations an order of magnitude smaller than today’s megacities and substantially lower domestic water withdrawals. Systems engineered for roughly one million residents cannot be incrementally scaled to serve ten million without failure at the network level. Unabated domestic water use is further aggravating demand. Between 1960 and 2014 domestic water withdrawals increased more than 600% (Otto and Schleifer 2020).

However, despite recognizing the value and adopting NbS and Blue–Green Infrastructure strategies as environmental solutions, multi-decadal evidence linking the creation of statutes and subsequent regulatory and governance framework aimed at measuring and improving water-quality and the spatial connectivity of water bodies is scarce. The clear environmental and socio-economic benefits and transition to hybrid systems is often hindered by socio-technical barriers and a lack of interdisciplinary consensus and understanding of non-engineered solutions among urban planners and engineers (Zuniga-Teran et al. 2020). A further barrier is paradigmatic: conventional engineering practice often treats hydrological and climatic boundary conditions as stationary, whereas ecological systems are inherently dynamic and generally unpredictable, so integrating ecological process knowledge and long-term trends into infrastructure design and planning are essential.

In this study, the Theory of Polycentric Governance (TPG) is advanced by moving beyond the conventional institutional interpretation toward an ecosystem where the physical and ecological infrastructure are aligned with society’s overarching goals, a process called infrastructure-centered operationalization. While Ostrom (2010) conceptualized polycentric systems as networks of overlapping decision-making centers that are capable of adaptive self-organization, the scholarship that subsequently followed critiqued this framework for its limited empirical tractability and reliance on qualitative institutional narratives (Carlisle and Gruby 2019; Morrison et al. 2019). To address these critiques, we reinterpret polycentric governance as a functional property of urban socio-technical systems, rather than solely on governance. Specifically, we argue that polycentricity can be empirically observed and measured when multiple infrastructural subsystems that operate at different spatial, temporal, and organizational scales, jointly contribute to system performance and resilience (Pahl-Wostl 2019). Within this framework, we differentiate the functional logic of the two subsystems.

It is important to delimit the scope of this integration. The framework advanced here is expert-led: it couples engineering, ecological, and governance knowledge, that is, academic and technical expertise, to render polycentricity operational through infrastructure. It therefore represents a partial, expert-side

variant of transdisciplinary sustainability research rather than its full form, which additionally requires the structured co-production of knowledge and solutions with non-technical societal actors such as residents, community organizations, and end-users (Lang et al. 2012). We adopt this narrower, infrastructure-centered lens deliberately, because our objective is to render polycentric governance empirically measurable through long-term biophysical system outcomes; integration of non-technical stakeholders is treated as a complementary dimension and revisited as a limitation below.

1.2 Theoretical Framework: Operationalizing Polycentric Governance through Hybrid Infrastructure

1.2.1 Grey Infrastructure is a monocentric functional logic that is a centralized, capital-intensive system that has been optimized for efficiency under stable conditions, yet these types of monolithic systems are vulnerable to temporal delays, lock-in effects, systemic shocks, and complete failure (Larsen et al. 2016).

1.2.2 Green Infrastructure (NbS) embodies a polycentric functional logic because it is decentralized, modular, and capable of rapid deployment, ecological self-organization, and adaptive buffering against climate extremes (Frantzeskaki 2019; Kabisch et al. 2017). Recent studies have demonstrated that hybridizing Green and Grey Infrastructure is significant because hybridized systems can substantially outperform mono-functional systems in terms of cost-effectiveness and adaptability (Bakhshipour et al. 2019). Rather than treating Green and Grey Infrastructure systems as binary systems, this study conceptualizes their interaction as Green–Grey Coupled Systems (Depietri and McPhearson 2017; Fig. 1).

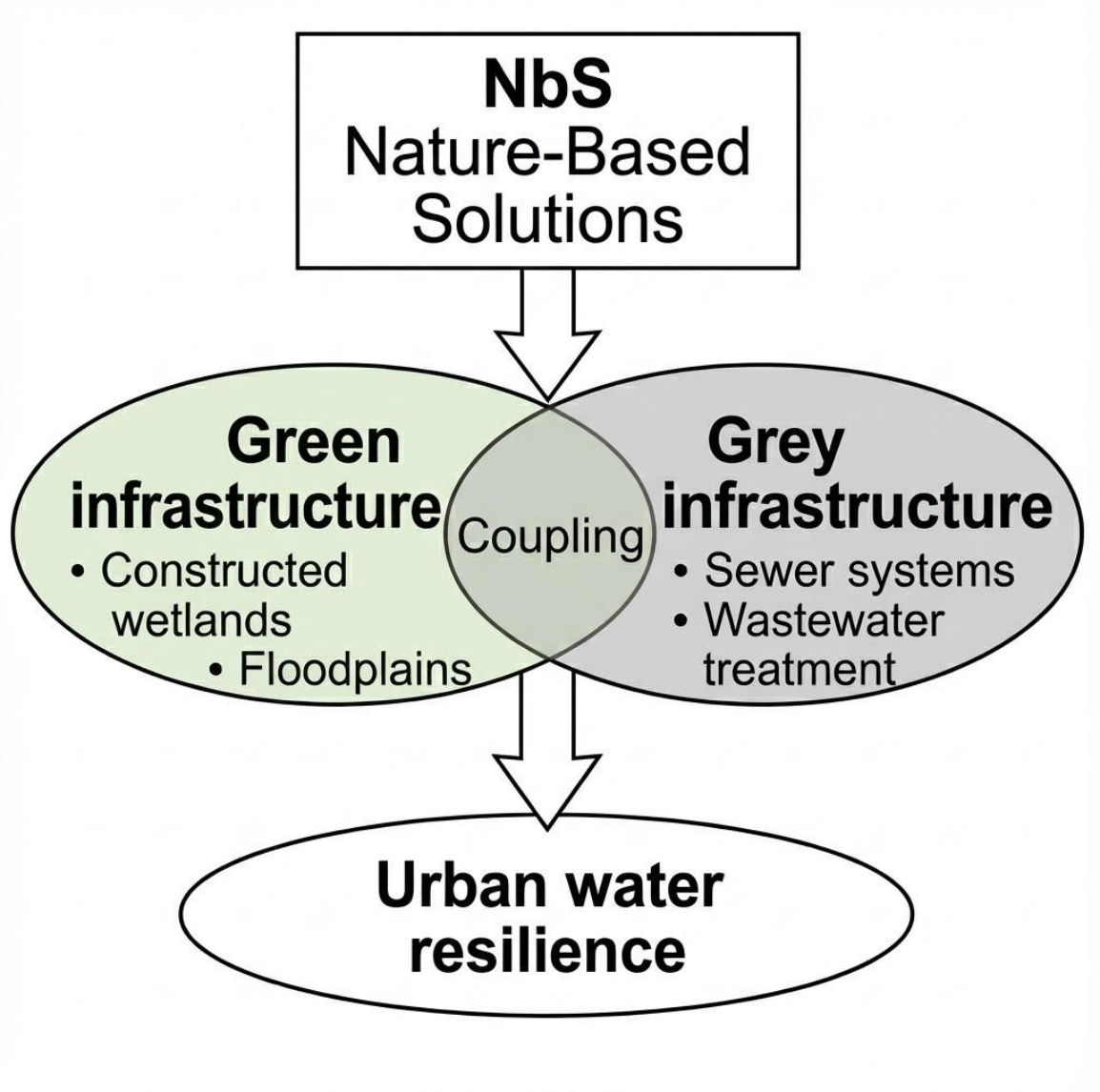


Fig. 1 Conceptual Framework of the Green–Grey Coupled System. Based on Ostrom's Polycentric Governance Theory, this study models the intersection of decentralized Green Infrastructure (Nature-based Solutions) and centralized Grey Infrastructure (Sewerage) as a "Coupling" zone. This hybrid approach generates urban water resilience by creating functional redundancy and overcomes the rigidity of monocentric systems

In this hybrid model, polycentric governance emerges through *functional complementarity*, *redundancy*, and *spatial embedding* (Andersson et al. 2014). This reframing allows polycentric governance to be empirically tested through measurable system outcomes such as water quality resilience and biodiversity recovery, rather than inferring the results from institutional designs alone.

1.3 Research Objectives

Despite the growing consensus on the benefits of NbS, empirical research bridging the gap between Governance Theory and engineering performance is fragmented. Three critical hypotheses in the current urban sustainability literature are addressed in this paper.

The hypotheses that were tested are as follows:

Hypothesis 1: Temporal Gap-filling demonstrates the wetlands mitigated pollution loads while the Grey Infrastructure was still under construction, improving water quality before sewerage coverage was completed (Section 3.1);

Hypothesis 2: Mature wetland ecosystems provide functional stability, sustain high pollutant-removal performance, expressed as a higher resilience index ($S = \mu/\sigma$), despite declining maintenance budgets and intensifying climatic disturbance (Section 3.3); and

Hypothesis 3: The physical and biological benefits of the Green–Grey network are bounded by a finite ecological service radius, producing a measurable belt-like influence on avian biodiversity (an estimated range of ~5.8 km) that yields explicit spatial-optimization rules for wetland siting (Figures 5 and 6).

1.3.1 Empirical Operationalization of Polycentric Governance

Existing scholarship on polycentric governance is often abstract or qualitative, lacking rigorous quantitative methodologies to assess system performance (Morrison et al. 2019; Thiel et al. 2019). By translating polycentricity from an institutional concept into quantifiable infrastructure functions such as pollutant removal resilience for example, this study provided a rare empirical test of Ostrom's theory in a large urban wetland ecosystem. We aimed to demonstrate how decentralized nodes collectively generated system-level resilience that exceeded the sum of the individual parts.

1.3.2 Elucidating the Temporal Dynamics of Green-Grey Coupling

While static comparisons of Green versus Grey Infrastructure abound, few studies examine their dynamic interaction over long temporal scales (Larsen et al. 2016). Using 30 years of data from 1994–2024, we examined how decentralized NbS served as transitional functional nodes, compensating for the deployment lag and rigidity of a centralized Grey Infrastructure system. This objective sought to validate the three hypotheses posited and quantify the hysteresis effect in ecosystem recovery (Scheffer et al. 2001).

1.3.3 Spatialization of Ecological Resilience Boundaries

Urban resilience is often treated as a unified or averaged city-wide metric, ignoring its spatially explicit heterogeneity (Meerow et al. 2016). Using Semivariogram Modeling, an advanced spatial statistic, we

161 defined the ecological sphere of influence that urbanization had on wetland biodiversity. This allowed us
162 to operationalize polycentric governance not just as an administrative construct, but as a spatially
163 distributed resilient network, providing scientifically grounded thresholds such as connectivity ranges for
164 urban planning (Cumming 2011).

165 ## 2. Materials and Methods

166 ### 2.1 Study Area and The Big Dig: A Socio-Technical Transition

167 The study focused on the Danshui River Basin (Basin), which is located in the Taipei Metropolitan Area.
168 This is a high-density urban agglomeration with a population of 7 million people in 2019. In 2004, the
169 former Taipei County Government (now New Taipei City initiated a massive ecological engineering
170 project known as the Big Dig, constructing 13 clustered wetlands along the riparian corridors within the
171 Basin to treat municipal wastewater and agricultural runoff (Fig. 2).

172 This initiative marked a decisive break in urban water management, moving from purely centralized grey
173 wastewater systems to functionally flexible decentralized, nature-based systems (Larsen et al. 2016). At
174 the time, the Basin had experienced severe ecological degradation due to substantial infrastructure
175 deficits, with low sewerage connection rates leaving raw domestic sewage as the primary pollutant load.
176 Constrained by the high capital costs needed to maintain or upgrade the existing infrastructural assets,
177 increase the capacity to manage the increasing amount of wastewater, and lengthy construction timelines
178 needed to build traditional centralized wastewater treatment plants (WWTPs), the administration adopted
179 an ecological engineering approach as a viable, cost-effective alternative (Oral et al. 2020).

180 The implementation strategy prioritized the adaptive reuse of the higher elevation floodplains located
181 along the river corridors, land previously neglected or degraded by illegal dumping. This approach
182 aligned with the principles of multifunctional Green Infrastructure, transforming underutilized distinct
183 spaces into active ecosystem service providers (Andersson et al. 2014). The construction process was
184 iterative and evidence-based, beginning with pilot projects to validate treatment efficacy before upscaling.

185 Critically, these wetlands were not merely excavated ponds; they were carefully engineered Free Water
186 Surface (FWS) systems designed with specific hydraulic retention times (HRT) and distinct physical and
187 ecological functional zones. Their design integrated deep settling basins for sedimentation, aeration
188 lagoons for oxygen transfer, and shallow marshes densely planted with emergent macrophytes such as
189 *Phragmites australis* (common reed) and *Typha orientalis* (bulrush) to phytoremediate pollutants. This
190 configuration optimized physical filtration, chemical adsorption, and biological nutrient uptake to
191 efficiently remove suspended solids (SS), biochemical oxygen demand (BOD), and nutrients like nitrogen
192 and phosphorus (Kadlec and Wallace 2008; Vymazal 2010). Ultimately, this undertaking transformed the
193 derelict riparian zones into the largest NbS constructed wetland network for water treatment in Taiwan,
194 demonstrating the scalability of decentralized infrastructure in densely populated metropolises, especially

in Asia. Independent international recognition corroborates this standing: the Dahan River wetlands are documented among 58 exemplary nature-based-solution projects worldwide in the U.S. Army Corps of Engineers' Engineering with Nature Atlas (Tritinger et al. 2024), positioning the cluster as an internationally recognized model of successful large-scale urban riparian restoration.

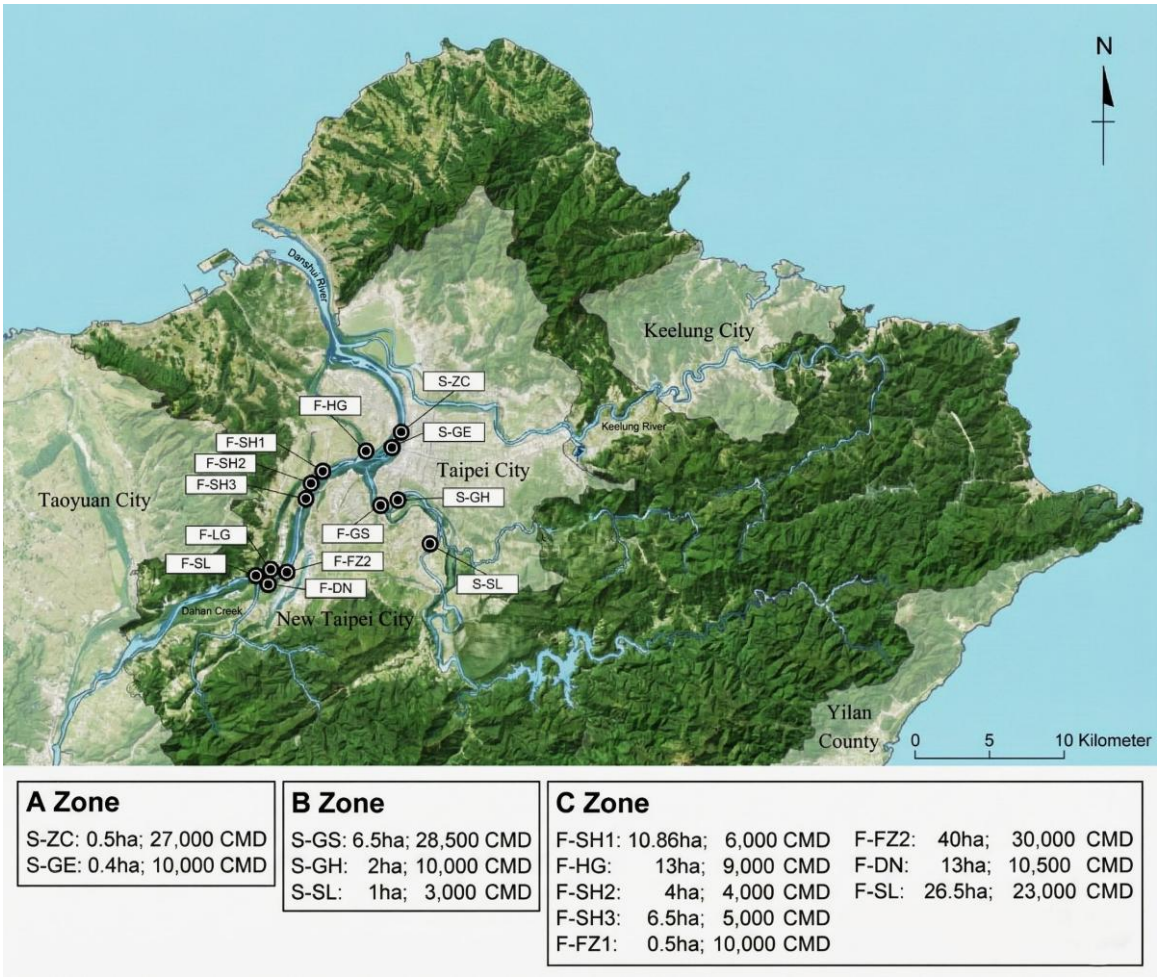


Fig. 2 Spatial distribution of the Green–Grey Infrastructure in the Danshui River Basin. The Danshui River Basin wetland complex is comprised of 13 constructed wetlands located along the Danshui River corridor. Detailed specifications for the three operational zones are as follows: A Zone (Upper Reach) consists of 2 wetlands (e.g., S-ZC, S-GE) with a combined capacity of 37,000 cubic meters per day (CMD); the B Zone (Middle Reach) has 3 wetlands (e.g., S-GS, S-GH, S-SL) totaling 41,500 CMD; and the C Zone (Lower Reach) has 8 wetlands with the largest capacity, including the F-FZ2 unit (40 ha, 30,000 CMD). This wetland complex treats approximately 176,000 CMD and functions as a decentralized buffer before the water reaches the centralized treatment plants

2.1.1 Spatial Configuration of the Polycentric Wetland Network

The intervention is operationally defined as a polycentric infrastructure network that is comprised of 13 distinct constructed wetlands (CW; Cheng et al. 2011) that are located along the main stem of the Danshui River and two of its major tributaries, Dahan and Xindian Creeks. In contrast to conventional monocentric WWTPs that rely on rigid, end-of-pipe discharge mechanisms (Larsen et al. 2016), these Green Nodes are strategically positioned at critical hydrological interface points, specifically at the confluence of urban drainage channels and the main body of the Danshui River (Fig. 2). This spatial topology served a dual function in the Basin's hydro-social hierarchy: a) Interception and Filtration: The wetlands act as semi-distributed buffers, intercepting non-point source runoff and combined sewer overflows (CSOs) before they enter the main river channel. This intercept-and-treat strategy effectively reduced shock loading (volume) and water velocity (erosive energy) during storm events, which addressed a critical weakness of centralized systems (Masi et al. 2018); b) Ecological Connectivity: Spanning a total area of approximately 300 ha, the wetlands function as ecological stepping stones in the fragmented riparian corridor. This configuration mitigated the isolation effects of the surrounding high-density Grey Infrastructure, effectively increasing landscape permeability for aquatic and avian species (Kong et al. 2010). Geographically, the network created a continuous green corridor, interconnecting aquatic, terrestrial and aerial habitats that extended from the upstream reaches of the Basin to the Danshui River tidal estuary, ensuring water quality improvements were cumulative as water flow progressed downstream. This distributed layout operationalized the concept of spatial redundancy (Ahern 2011), ensuring that the failure or poor maintenance of a single node did not compromise the functional resilience and value of the entire riparian purification ecosystem.

2.1.2 Data Sources and Hydro-Environmental Characteristics

A comprehensive, high-resolution dataset integrating three decades (1994–2024) of environmental monitoring and infrastructure development records of the Basin was used in this study. To evaluate the systemic impact of the wetland network, water-quality samples were drawn from 38 monitoring stations distributed across the Basin (yielding the 17,564 parameter-records summarized in Table 1). The analysis of these samples focused on four critical water-quality parameters that comprised the River Pollution Index (RPI), which is a standard metric for assessing urban river health in Taiwan (River Pollution Index, RPI; Taiwan Ministry of Environment, formerly EPA; computed following Liou et al. 2004). The parameters include: Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), Suspended Solids (SS), and Ammonia Nitrogen (NH_3-N). These parameters were selected because they are reliable proxies for organic loading, ecosystem oxygenation status, and physical turbidity (Chang et al. 2018).

Two features of the record require checking before any period comparison is made, because a panel assembled over three decades can change in ways that mimic the effect under study (Wooldridge 2010). The first is sample composition. All 38 stations report in both the early (1994–1999) and late (2019–

2024) windows, so no station enters or leaves between the compared periods and the comparison rests on a balanced set. The second is measurement definition, and here the record does change: dissolved oxygen was determined using titration methodology until 2010 and by electrode from 2011 onward, with the two methods running in parallel between 2002 and 2010. That overlap permits a direct test. Across 3,050 samples measured by both methods, the electrode reading exceeds the titrimetric reading by 0.041 mg L^{-1} on average ($r = 0.993$), which is 2.5% of the 1.66 mg L^{-1} improvement reported in Table 2. The instrument change is therefore real but too small to generate the observed signal. Ammonia nitrogen, biochemical oxygen demand and suspended solids were determined by a single method throughout.

The descriptive statistics from 17,564 parameter-records are summarized in Table 1. Over the 30-year period, the Basin exhibited a moderate level of pollution. The average RPI and DO values were 3.46 and 6.01 mg/L, respectively, suggesting the baseline conditions were generally supportive of aquatic respiration. However, the descriptive statistics revealed significant temporal heterogeneity: a) Organic Loading Variability: The range in NH_3-N (0.00–50.00 mg/L) and BOD (0.02 – 337.00 mg/L) were substantial and highlight the historical legacy of untreated sewage discharge and occasional severe pollution events prior to the creation of the wetlands; b) Hydro-Climatic Disturbances: The extremely high standard deviation observed for SS (Mean = 105.7 mg/L; SD = 490.5 mg/L) reflects the Basin's distinct subtropical hydrological regime. Specifically, the system was subject to pulse disturbances driven by typhoons and extreme rainfall events (Huang et al. 2012). These events triggered massive sediment runoff and non-point source flushing, causing short-term but extreme spikes in turbidity and pollutant concentrations that challenged the resilience of conventional treatment infrastructure (Zeng et al. 2020). Sewerage-connection statistics were obtained from the Public Works Department, New Taipei City Government (2024).

Table 1: Overall Descriptive Statistics (1994–2024)

Parameter	number	Mean	SD	Min	Max
River Pollution Index (RPI)	17,564	3.46	2.18	1.00	10.00
Dissolved Oxygen (DO mg/L)	17,564	6.01	3.09	0.00	19.20
Biochemical Oxygen Demand (BOD mg/L)	17,564	3.78	5.70	0.02	337.00

Parameter	number	Mean	SD	Min	Max
Suspended Solids (SS mg/L)	17,564	65.06	490.50	0.00	20,000.00*
Ammonia Nitrogen (NH_3-N mg/L)	17,564	1.73	2.43	0.00	50.00

Note: The extreme maximum value for SS reflects sediment transport during typhoon-induced storm surges.

2.2 Statistical Verification of Resilience Enhancement and Regime Shift

To quantitatively verify the efficacy of the Green–Grey Infrastructure network, we conducted a rigorous statistical comparison between the baseline reference state (Early Period: 1994–1999) and the mature operational state (Late Period: 2019–2024). This temporal segmentation allowed us to perform a robust assessment of the system's development following long-term pollution control interventions. Our analyses yielded compelling empirical evidence of a structural regime shift in the Basin's hydro-chemical profile through time (Table 2). Two-sample *t*-tests confirm that all key resilience indicators exhibited highly significant divergences ($p < 0.001$), decisively rejecting the null hypothesis (this test operationalizes H2: the null of no difference in resilience indicators between the early and late periods is evaluated against the alternative of a measurable green–grey regime shift) that the processes occurring in the wetlands were static. Key statistical findings include:

***2.2.1 Pollution Abatement (RPI)*:** The RPI demonstrated a remarkable reduction of 1.75 units ($t = -32.15$; 95% CI [-1.86, -1.64]). This metric confirmed a fundamental transition from a moderately polluted to a lightly polluted state, suggesting that the Basin has crossed a critical threshold towards ecological recovery (Wang et al. 2018).

***2.2.2 Dissolved Oxygen (DO) and Ecological Recovery*:** The DO concentrations increased by an average of 1.66 mg/L ($t = 21.85$; 95% CI [1.51, 1.81]). This substantial increase indicates restoration of the river's aerobic metabolic capacity, a prerequisite for supporting higher aquatic and terrestrial trophic level biodiversity.

***2.2.3 Organic and Physical Load Attenuation*:** The system achieved a significant reduction in BOD of 2.35 mg/L ($t = -12.75$), reflecting the effective removal of biodegradable organic matter. Furthermore, the amount of SS decreased by 40.22 mg/L ($t = -6.95$), indicating that the wetland network was successfully buffering turbidity spikes and sediment runoff.

These results provide robust confirmation that the Basin had achieved a statistically significant increase in ecological resilience. The data suggest that the integrated infrastructure effectively decoupled the pressure of urbanization from environmental degradation, establishing a new, more ecologically desirable and stable domain over the past three decades (Folke et al. 2004; Xue et al. 2015).

Table 2: Comparison between the Early Period (1994-1999) and the Late Period (2019-2024) to verify the statistically significant increase in resilience (water quality improvement).

Parameter	Mean Difference (Late - Early)	t-statistic	p-value	95% CI	Result
RPI	-1.75	-32.15	< 0.001	[-1.86, -1.64]	Significant Decrease (Improved)
DO	+1.66	+21.85	< 0.001	[1.51, 1.81]	Significant Increase (Improved)
BOD	-2.35	-12.75	< 0.001	[-2.71, -1.99]	Significant Decrease (Improved)
SS	-40.22	-6.95	< 0.001	[-51.56, -28.87]	Significant Decrease (Improved)

2.3 Analytical Methods: A Coupled Spatiotemporal Framework

Following the characterization of spatio-temporal variability in the monitoring dataset, a multi-tiered analytical framework was used to assess the system's structural stability. Given the observed fluctuations driven by extreme hydrological events (e.g., typhoons), standard descriptive statistics alone were insufficient to evaluate the true recovery trajectory of the wetland ecosystems. To accurately assess the efficacy of coupling Green and Grey Infrastructure over a 30-year period, we introduced a quantitative approach that integrated temporal stability analysis with spatial geostatistics. This framework measured the river's capacity to maintain water quality functionality amidst environmental disturbances and quantified the Basin-wide transition towards a resilient state.

2.3.1 Engineering Resilience (^{R}): Quantifying Long-term Stability

We began by establishing a baseline metric for temporal stability because the standard descriptive statistics, while useful for identifying trends, did not capture the dynamic capacity of a system to absorb

disturbances without losing functionality. To quantify the stability of the water purification system over time, we adopted a Normalized Engineering Resilience index (R_e).

Unlike traditional definitions that rely solely on recovery time (Holling 1973), we operationalized resilience as the inverse of hydrological variability, normalized to a bounded scale. Specifically, we defined R_e as an exponential function of the Coefficient of Variation (CV), representing the system's ability to maintain its function relative to disturbance-driven fluctuations: For consistency with the index reported in the Abstract and in Section 3.3, resilience is defined as the inverse coefficient of variation, S = μ/σ (the ratio of the long-term mean to its standard deviation), so that higher values denote greater temporal stability (a higher signal-to-noise ratio).

$$S = \mu/\sigma \quad (1)$$

Where:

- μ is the mean concentration of the water quality parameter (e.g., DO, BOD) over a defined phase; and
- σ is the standard deviation, representing the magnitude of response to environmental shocks.

This approach is reported throughout on a single, consistent definition (S = μ/σ); higher values denote greater temporal stability, and we interpret relative differences between phases rather than absolute ceilings (Hashimoto et al. 1982; Tilman 1996). Recent system analyses support the use of normalized variability metrics to quantify multidimensional stability (Donohue et al. 2016). This approach allowed a robust cross-parameter comparison that can be interpreted as follows: a) For beneficial parameters (e.g., DO): A high R_e value combined with an increasing mean (μ) indicates a robust, oxygen-rich environment capable of buffering hypoxic events; b) For pollutants such as NH_3-N and SS, a high R_e value indicates stability against spikes. It's important to note that calculating the CV for values approaching detection limits can be mathematically sensitive, which is often referred to as the small mean problem where denominators near zero inflate variability. To address this, we interpreted resilience for pollutants using a dual-criteria framework. Within the context of urban river management, a truly resilient state is strictly defined by the joint achievement of load reduction ($\mu\downarrow$) and stability enhancement ($R_e\uparrow$). This rigorous approach ensured that we distinguished true ecological stability from low-concentration noise, which signifies a system that has effectively dampened the impact of pulse disturbances and a high predictability and resistance to shock loadings.

2.3.2 Deepening the Analysis: Resistance to Pulse Disturbances (Ω)

While R_e provided a necessary macroscopic view of chronic stability, it's insufficient for diagnosing acute system responses. Reliance on variability metrics alone represents a coarse-grained approach that may obscure the specific mechanistic response to extreme pulse disturbances, such as typhoons or torrential rains, which are characteristic of a subtropical hydro-climate (Zeng et al. 2020). To address this limitation and capture the full multidimensionality of ecological stability, we advanced the framework by introducing a secondary metric: Resistance (Ω). Drawing on Pimm's (1984) Foundational Stability Theory and recent syntheses by Donohue et al. (2013), Ω resistance is defined not by the variance over time, but by the system's capacity to withstand maximum displacement during a shock event.

We operationalized this concept using the Resistance Index (Ω), which is calculated as the ratio of the baseline state to the magnitude of disturbance-induced displacement: This Resistance metric (Ω) is distinct from the Resilience index (R) defined above: R quantifies chronic temporal stability whereas Ω quantifies acute resistance to discrete shock events; these were the only two stability constructs used in this study.

$$\Omega = \frac{\mu_{baseline}}{|\mu_{baseline} - Y_{shock}|} \quad (2)$$

Where:

$\mu_{baseline}$ is the mean concentration of the water quality parameter during the non-typhoon (baseflow) period.

Y_{shock} represents the extreme value recorded during identified peak disturbance events (e.g., typhoon landfall $+24$ hours).

$|\mu_{baseline} - Y_{shock}|$ is the displacement or the absolute deviation from the baseline state.

Interpretation:

Unlike R_e, which measures general consistency, Ω specifically diagnosed the absorptive capacity of the infrastructure. A higher Ω value indicates that the Green-Grey coupled system buffers the shock better than infrastructure possessing a lower Ω value, preventing catastrophic failure, such as hypoxia or

367 massive sediment resuspension despite extreme external loading. This multi-tiered mathematical
368 framework, combining R_e for chronic stability and Ω for acute resistance, ensured a comprehensive
369 diagnosis of the basin's hydro-ecological health under climate change scenarios.

370 ***2.3.3 Spatial Statistics (Avian Bio-indicators and Ecological Impact)***

371 Having established the temporal resilience of the system, we next turned to its spatial dimension. While
372 the temporal resilience metrics (R_e and Ω) quantified the system's stability over time, understanding the
373 geographic extent of these improvements required a spatially explicit assessment. To evaluate the spatial
374 resilience of the wetland network and determine whether the observed improvements were localized or
375 Basin-wide, we integrated long-term avian survey data as a proxy for high-trophic-level ecosystem health
376 (Callaghan et al. 2021).

377 We treated bird species richness and diversity as regionalized variables $Z(x)$ to model the spatial
378 continuity of ecological recovery. The geostatistical methods employed included: a) Local Indicators of
379 Spatial Association (LISA) to identify the functional green nodes within the urban matrix. LISA was used
380 to detect spatial clusters of high biodiversity (High-High clusters) and diagnose ecological outliers (High-
381 Low) where wetland performance deviated from the neighborhood context (Anselin 2019; Li et al. 2020);
382 and b) Indicator Kriging (IK) and Semivariogram Modeling: To estimate the spatial extent of urban
383 disturbance and define the range of influence of wetland habitats, we calculated the experimental
384 semivariogram using Eq. (3): (Anselin 1995).

385 $$\gamma(h) = \frac{1}{2} E[Z(x) - Z(x+h)]^2 \quad (3)$$

386 Where $\gamma(h)$ is the semivariance, $Z(x)$ is an ecological indicator such as the Shannon Index at location
387 x, and h is the lag distance. We fitted the Spherical and Exponential Models to determine the Range
388 (a), which physically represents the distance that ecological spatial autocorrelation disappears, which
389 effectively quantifies the ecological service radius or the impact zone of urban disturbances (Strohbach et
390 al. 2019).

391 ***2.3.4 Ecological Interpretation: Deriving Spatial Governance Rules***

Finally, we translated these geostatistical findings into actionable planning criteria. As illustrated in the semivariogram analysis that is presented in Section 3.4, the spatial autocorrelation for avian species richness extends to a range of approximately 5.85 km (Exponential Model). This specific geostatistical metric is critical for urban spatial planning because it effectively quantifies the Ecological Service Radius of the wetland nodes within the hostile urban matrix.

The 5.85 km threshold delineates the spatial extent of ecological influence. Beyond this range, the positive spatial dependence of species richness decays, suggesting that the urban Grey Infrastructure exerts a fragmented pressure that disrupts ecological flows (Cumming 2011). In the context of metapopulation dynamics, this implies that wetland patches separated by distances greater than 6 km begin to function as isolated islands rather than a cohesive interconnected network, severely limiting the habitat and dispersal of sensitive avian species (Kong et al. 2010).

Accordingly, we formalized three testable hypotheses, each aligned with a specific analysis and figure: H1 (Temporal Gap-Filling): decentralized wetlands measurably substitute for centralized capacity during the construction lag, improving water quality while sewerage coverage remains low (Section 3.1); H2 (Redundancy-Induced Stability): functional redundancy between Green and Grey subsystems raises system resilience and lowers variability from the construction to the maturation phase (Section 3.3); and H3 (Hydrological Recoupling): in-stream wetland retention buffers baseflow depletion caused by centralized interception (Section 4.4).

Consequently, to maintain a resilient wetland network, a scientifically grounded Spatial Governance Rule is proposed. That is, the inter-nodal spacing between the functional Green Infrastructure nodes must be maintained below the 5.8 km threshold. This distance ensures the functional connectivity of the nodes, allowing the constructed wetlands to serve as effective stepping stones that facilitate avian species habitat establishment, movement, and gene flow across dense metropolitan areas. This finding provided a rigorous quantitative basis for defining the necessary density of the polycentric Green Infrastructure network, moving beyond arbitrary zoning to evidence-based landscape configuration (Andersson et al. 2014; Mitchell et al. 2015).

Applying the coupled spatiotemporal framework defined in Section 2, the empirical evidence of the system's structural transformation over the 30-year study period is now presented. The results are organized to mirror the theoretical dimensions of polycentricity: temporal adaptation, functional redundancy and spatial connectivity, thereby grounding the governance concept in technically defensible hard data.

To respond to longstanding critiques that polycentric governance lacks methodological rigor, this study explicitly aligned each theoretical proposition with a corresponding analytical metric. Temporal

polycentricity was evaluated through infrastructure gap analysis and resilience indices; functional polycentricity was assessed via cost-efficiency and redundancy effects; and spatial polycentricity was quantified using geostatistical diagnostics of ecological buffering capacity. This theory–method coupling ensured that polycentric governance was not inferred *post hoc*, but systematically tested through observable system behavior.

As a foundational step, we first examined the descriptive statistics of the system's evolution. Table 3 compared the hydro-chemical baseline of the implementation phase (Phase I) against the mature operational phase (Phase II), revealing the broad trends of water quality improvement that was driven by the clustered wetland network.

Table 3. Descriptive statistics of key water quality parameters (NH_3-N and DO) compared between Phase I (2004–2012) and Phase II (2013–2024).

Parameter	Phase	Mean	SD	Min	Max	number
NH_3–N (mg/L)	Phase I (2004–2012)	1.59	2.13	0.01	15.40	3,939
	Phase II (2013–2024)	1.11	1.55	0.01	15.00	5,471
DO (mg/L)	Phase I (2004–2012)	6.53	3.07	0.00	19.20	3,940
	Phase II (2013–2024)	6.67	2.91	0.10	18.70	5,471

Note: Sample sizes (n) differ slightly between parameters in Phase I due to a single missing Ammonia Nitrogen measurement in the historical record.

3. Results: Empirical Validation of the Polycentric Model

The following sections present the empirical evidence of the system's structural transformation, moving from temporal functional substitution to long-term systemic resilience, and finally defining the spatial boundaries of ecological governance.

3.1 The "Grey Gap" and Green Substitution (2004–2012)

The initial phase of the analysis addressed the temporal mismatch, which is inherent in large-scale infrastructure projects. Analysis of the sewage connection data revealed a significant infrastructure lag. In 2004, when wetland construction began, New Taipei City's public sewage connection rate was negligible ($<10\%$). By 2012, despite massive investment, it only reached approximately 33% (Fig. 3).

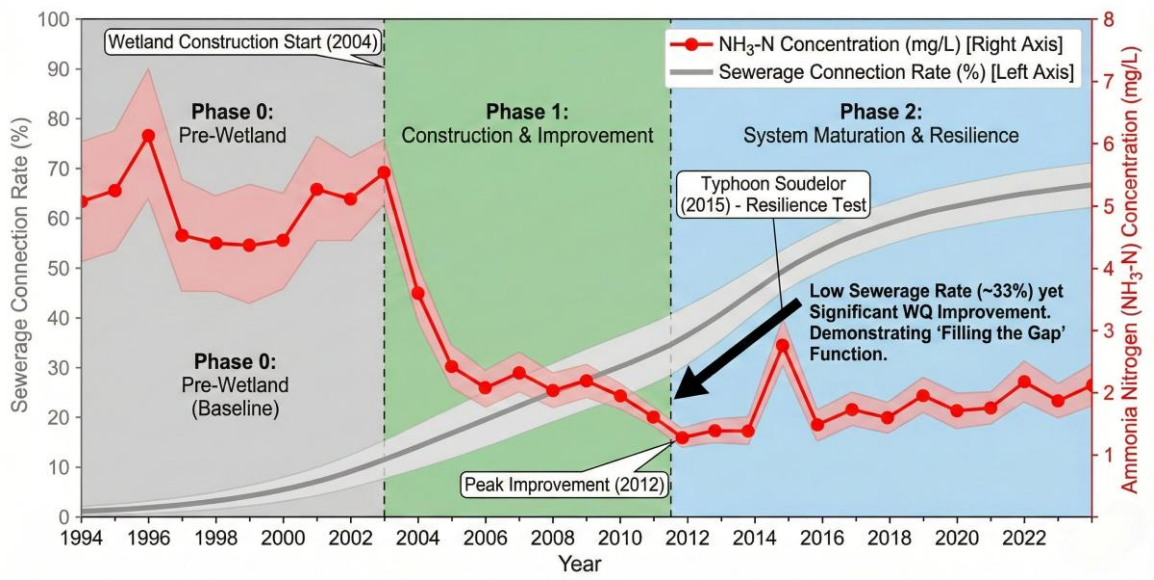


Fig. 3 The "Gap-Filling" Phenomenon (1994–2024). The red line represents riparian Ammonia Nitrogen (NH_3–N) concentrations, while the grey shaded area is the public sewerage connection rate. Phase I (Construction): Note 2004–2012, the critical time where sewerage rates were low (~33%), yet water quality improved significantly (NH_3–N dropped from ~5.0 to 1.3 mg/L). This visually validates Hypothesis 1, which is Hypothesis I: Temporal Gap-filling demonstrating that the wetlands mitigated pollution loads while the Grey Infrastructure was still under construction

This discrepancy highlights a critical Grey Gap Paradox. Despite more than 50% of household wastewater remaining untreated by centralized Grey Infrastructure, river water quality improved dramatically during this period. The mechanism driving this decoupling was the functional substitution provided by the polycentric wetland network. The 13 constructed wetlands treated approximately 176,000 cubic meters per day (CMD) of wastewater, acting as a decentralized buffer.

The monitoring data confirmed that river NH_3-N dropped from a peak of 5.0 mg/L (2003) to ~1.3 mg/L (2012). These findings provided direct empirical support for the Gap-Filling hypothesis or said another way, the Green Infrastructure provided critical sanitation services while the Grey Infrastructure was still under construction. Theoretically, this validated Ostrom's proposition that polycentric systems outperform monocentric regimes under conditions of uncertainty. Here, polycentric governance is demonstrated not merely through institutional plurality, but through temporal functional substitution embedded in the hybrid infrastructure design.

3.2 Long-term Resilience and Cost-Effectiveness (2013–2024)

Following the successful bridging of the infrastructure gap, the system's role evolved, becoming more efficient. Post-2013, as the Grey Infrastructure coverage expanded, reaching $> 72\%$ in New Taipei by

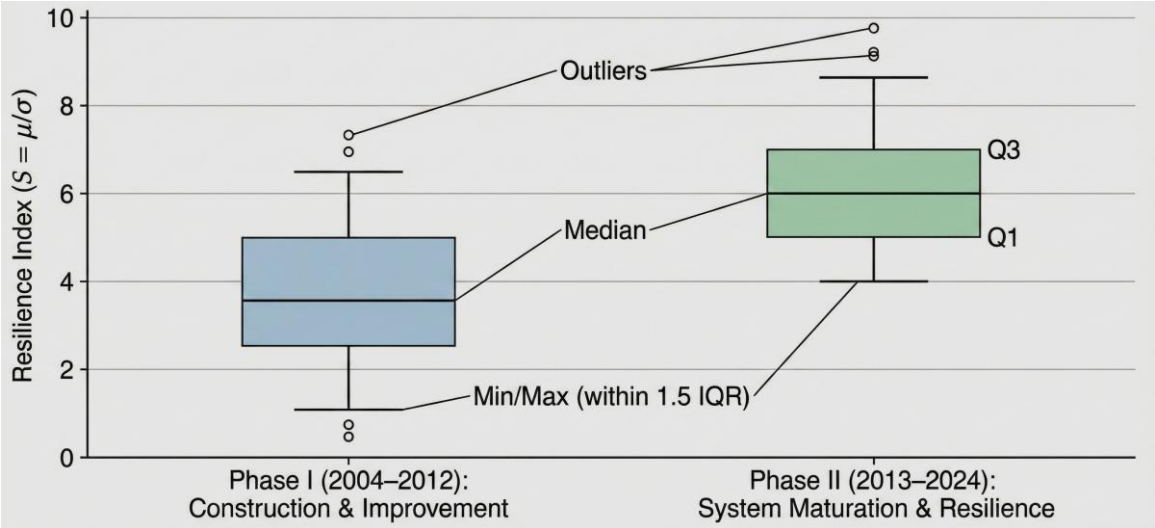
2024, the wetland network transitioned from a primary treatment provider to a polishing and resilience buffering system.

3.3 Statistical Verification of Resilience

To verify whether this transition represented a genuine enhancement in stability, we conducted a rigorous statistical comparison between Phase I and Phase II (Table 3). Between these phases the descriptive statistics (Table 3) show NH_3–N declining from 1.59 to 1.11 mg L^{-1} and DO rising from 6.53 to 6.67 mg L^{-1}. Formal two-sample testing of the early (1994–1999) versus late (2019–2024) reference states (Table 2) confirm the statistically significant change across all four pollution indicators: RPI (−1.75), BOD (−2.35), and SS (−40.22) decreasing and DO (+1.66) increasing (all $p < 0.001$). These results provided robust evidence that the improvements observed were not due to random variability but represent a statistically significant increase in the river's resilience against pollution loads (Fig. 4).

This functional resilience is underpinned by high cost-efficiency. The total construction cost for the wetland system was $33.7 million USD. Crucially, the operational cost for BOD removal in wetlands ($0.42 - 3.62 / kg$) was found to be comparable to the mid-range of traditional wastewater treatment plants ($1.18 / kg$). A more detailed assessment of the capital and maintenance costs of centralized versus decentralized systems is underway and will be presented in another paper. On a per-kilogram basis the wetlands therefore fall within the conventional plant range (US$0.42–3.62 kg^{-1} BOD), which itself varies with plant scale, treatment train, and energy prices; the decisive advantage of the green option lies in capital cost (≈10–15% of grey alternatives) and in co-benefits not captured by unit treatment cost.

The phytoremediation of organic and inorganic (metals and metalloids) constituents of concern (COCs) is an obvious co-benefit of clustered wetland ecosystems. As cities grow, wastewater volumes rise and emerging chemicals that include pharmaceuticals and nanoparticles will become more prevalent. Constructed wetland that are designed to address these types of contaminants can and should be incorporated in megacity clustered wetlands. A detailed discussion of these concepts far exceeds the scope of the current paper and will be the topic of papers to follow.



Note: Higher S values indicate greater system stability and resilience. Phase II shows a statistically increase in median resilience and reduced variability compared to Phase I.

Fig. 4 Comparative Resilience Analysis ($S = \mu / \sigma$) between Phase I and Phase II:

Redundancy-Induced Stability. The boxplot illustrates a statistically significant increase in the Resilience Index (S) from the Construction Phase (2004–2012) to the Maturation Phase (2013–2024). Higher S values indicate greater functional stability (lower coefficient of variation) despite external shocks such as typhoons, supporting Hypothesis II regarding the stabilizing role of mature ecosystems

Furthermore, comparison of the Phase I (2004–2012) and Phase II (2013–2024) Resilience Index (R_e) for DO show an increase in the DO, indicating the system became more stable over time despite reduced maintenance budgets. This pattern is consistent with hysteresis-like behavior (Fig. 4), in which the established ecosystems maintained high functionality with lower energy inputs, effectively locking in the resilient state.

Resistance to acute shock was quantified following, Typhoon Soudelor (August 2015), the most severe storm event on record. Using the maturation-phase baseline (NH_3–N μ = 1.11 mg L^{-1}; Table 3) and the storm-driven riparian peak (≈ 2.8 mg L^{-1}; Fig. 3), the Resistance Index was calculated as follows: Ω = μ baseline / |μ baseline – Y shock| ≈ 0.66. A value below unity indicates that the instantaneous perturbation displaced the mean by roughly 1.5 times the baseline before the network returned to its pre-shock state, so the system exhibited limited resistance to the acute shock but high engineering resilience, recovering rapidly rather than resisting displacement, consistent with the redundancy-induced stability reported above. Event-resolved Ω values for the full set of monitored typhoons remain to be tabulated from the authors' high-frequency record.

3.4 Spatial Diagnosis of Ecological Resilience

While the temporal analysis confirmed the system's hydrological stability and cost-effectiveness, it did not define the geographical extent of these benefits. To address this, we employed spatial statistics on avian populations to define quantitative boundaries for the ecological buffer zones in the high-density urban environment.

Fig. 5 presents the Semivariogram Modeling results, offering critical insight into the spatial conflict between wetland habitats and urban infrastructure. The plot clearly illustrates the distinct spatial structures of two ecological indicators: a) Biodiversity (Shannon Index): The spatial variation was best described by a Spherical Variogram Model ($R^2 = 0.82$), revealing a distinct disturbance range of 4,440 meters (solid blue line in Fig. 5). This indicated urban expansion vectors such as impervious surfaces and noise exerted a strong de-correlation effect on biodiversity of up to 4.4 km from the source; b) Species Richness: Modeled with an Exponential Variogram ($R^2 = 0.744$), species richness exhibited a wider, belt-like disturbance range of 5,850 meters (dashed red line in Fig. 5). This suggests large-scale stressors such as industrial zones, can impact species composition and functional redundancy up to nearly 6 km away (Filazzola et al. 2019).

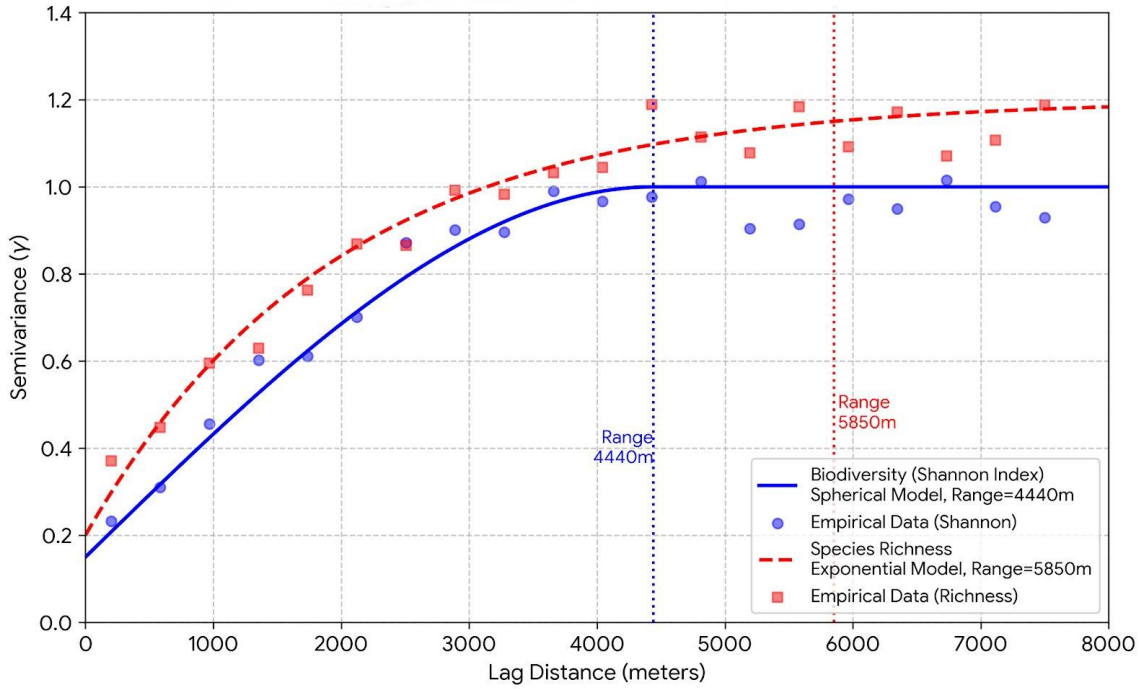


Fig. 5 Semivariogram Modeling results for avian ecological indicators in the high-density urban environment. Points represent empirical semivariance estimates. The solid blue curve shows the Spherical Model fitted to Biodiversity (Shannon Index), indicating a spatial range of 4,440 m. The dashed red curve represents the Exponential model fitted to Species Richness, revealing a wider practical range of 5,850 m. The vertical dotted lines mark these critical ranges, visually demarcating the spatial extent of urban disturbance on different ecological facets

Fixing these thresholds quantitatively is what makes spatial diagnosis possible. Consistent with spatial-planning studies in sustainable cities that translate ecological patterns into actionable urban design criteria, we interpreted the semivariogram range as an operational connectivity threshold for green-node spacing (Ganjirad et al. 2025). The analysis revealed that while general biodiversity is impacted up to 4.4 km from the disturbance sources, species richness is sensitive to a wider impact zone. Therefore, the wider range of approximately 5.8 km serves as the critical baseline distance for defining ecological buffer zones. Defining spatial thresholds is critical, as the fragmentation of green spaces can severely limit their ecological and social co-benefits (Fan et al. 2023). Consequently, to ensure ecological connectivity and maintain a resilient wetland network, the spacing between functional Green Infrastructure nodes must be kept below this 5.8 km threshold.

3.5 Synthesis: Ecological and Governance Implications

Synthesizing the geostatistical findings with the governance framework, these quantitative ranges challenge traditional administrative-based zoning. The data imply that the urban Grey Infrastructure exerts a disturbance pressure that fragments bird populations over a 6-km radius. Repeating our analyses using data on mammals, reptiles, amphibians, insects, and plants will inevitably provide additional

553 valuable data that urban planners will require to reconstruct and incorporate natural habitats in the design
554 of future cities.

555 By quantifying these ecological buffer ranges, this study extended Polycentric Governance Theory into
556 the spatial domain. We demonstrated that resilience in urban socio-ecological systems depends on
557 institutional diversity (those who manage the wetlands) and, equally, on the geographical configuration
558 (spacing and connectivity) of decentralized functional nodes. Specifically, wetland systems spaced no
559 more than 5.8 km from one another can form a functionally interconnected resilience corridor, whereas
560 those spaced further apart risk becoming isolated ecological islands. This finding provided a rigorous
561 scientific basis for mandating evidence-based landscape configuration in future urban planning.

562 4. Discussion: Integrating Hybrid Infrastructure and Polycentric Governance for
563 Urban Water Sustainability

564 This study employed a unique 30-year longitudinal dataset (1994–2024) to empirically examine how
565 hybrid Green–Grey Infrastructure systems contribute to urban water sustainability in a high-density
566 subtropical megacity. Drawing on Elinor Ostrom's Theory of Polycentric Governance (Ostrom 2010) and
567 socio-technical transition frameworks (Geels 2011), we interpreted Taipei's urban water transition not as
568 a linear engineering upgrade, but as an evolving socio-ecological regime. In this regime, multiple,
569 overlapping infrastructural and institutional centers jointly shape and improve system performance.
570 Decentralized polycentric clustered wetland ecosystems will not only help achieve water sustainability
571 and ecosystem preservation efforts, catastrophic system failures will likely be avoided.

572 Rather than framing centralized sewerage (Grey) and decentralized solutions (NbS/Green) as competing
573 dichotomies, our analysis demonstrated that their coupling generated complementary functions across
574 space and time (Depietri and McPhearson 2017). By integrating spatial configuration, temporal water-
575 quality dynamics, and resilience metrics, we provided empirical evidence that constructed wetlands
576 functioned as critical infrastructural assets in a polycentric urban water regime.

577 We argue that infrastructure alone does not constitute governance; rather, polycentricity is an emergent
578 system property arising from the interaction between institutional arrangements and infrastructural design.

579 4.1 Socio-Spatial Embedding of Nature-Based Solutions

580 Fig. 1 illustrates the spatial distribution of 13 constructed wetlands across the Basin, overlaid with
581 population density. Their concentration in densely urbanized corridors highlights a central challenge of
582 contemporary urban sustainability: reconciling ecological function with intense anthropogenic pressure
583 (Haase et al. 2014).

584 This spatial configuration suggests that wetlands in Taipei are not peripheral green amenities but
585 embedded socio-ecological nodes in a metropolitan core. Their deliberate placement in high-stress urban

586 zones reflects a strategic governance choice to internalize ecological remediation within the areas that
587 generate the greatest environmental load. This type of embedding aligns with polycentric governance
588 principles, where localized, context-specific interventions complement centralized systems rather than
589 operating at the urban fringe (Andersson et al. 2014).

590 **4.2 Temporal Dynamics and Transitional Infrastructure Roles**

591 The thirty-year NH_3-N trajectory (Fig. 3) reveals distinct phases of water-quality transformation that
592 challenge static interpretations of system-level performance. The most pronounced improvement occurred
593 during Phase I (2004–2012), coinciding with the rapid deployment of constructed wetlands, while
594 sewerage connection rates remained below 40%.

595 The dual-axis coupling analysis (Fig. 3) further clarifies this temporal mismatch. Centralized sewerage
596 expansion followed a capital-intensive and path-dependent trajectory, with measurable ecological benefits
597 lagging behind investment (Larsen et al. 2016). In contrast, decentralized wetlands delivered nearly
598 immediate pollution reduction, effectively functioning as transitional infrastructure that bridged
599 performance gaps during periods when monocentric systems were unable to respond rapidly.

600 This finding empirically substantiates Ostrom's argument that institutional and infrastructural diversity
601 enhances adaptive capacity. Polycentric systems enable timely interventions that mitigate environmental
602 degradation before centralized infrastructure reaches full operational maturity (Morrison et al. 2019).

603 **4.3 From Remediation to Resilience through Functional Redundancy**

604 Beyond short-term remediation, Fig. 4 demonstrates a substantial and significant increase in system
605 resilience from Phase I to Phase II, as measured by the Resilience Index ($R_e = \exp(-CV)$). The
606 improvement is twofold: mean water-quality performance rose, and temporal variability fell under
607 hydrological disturbances such as typhoons and droughts. Although simplified, this metric captures a core
608 dimension of socio-ecological resilience: the capacity to remain functional during disturbance regimes,
609 which is widely recognized as a necessary condition of broader adaptive resilience (Folke et al. 2016).

610 Conventional socio-technical paradigms often interpret redundancy as inefficient. However, our results
611 confirmed that functional redundancy between the Green and Grey Infrastructure enhanced system
612 stability (Ahern 2011). After 2013, diminishing marginal returns from further sewerage expansion
613 became evident, while overall water-quality stability was maintained despite reduced wetland
614 maintenance budgets. This indicates that Green–Grey coupling created a systemic safety net, allowing
615 one subsystem to absorb shocks when the other was stressed. Such dynamics illustrate how polycentric
616 infrastructure configurations generate resilience through diversity, overlap, and partial substitutability, all
617 key attributes for urban systems facing increasing climatic uncertainty.

4.4 Recoupling Hydrological Processes through Hybrid Infrastructure

Fig. 1 synthesizes these findings into a conceptual Green–Grey synergy model. Centralized wastewater treatment, while effective in pollutant removal, often diverts water away from river channels via marine outfalls, inadvertently reducing baseflow and seasonal dilution capacity (Walsh et al. 2012).

Constructed wetlands operate differently. By treating and retaining water within the river corridor, they function as in-stream nodes that recouple hydrological processes disrupted by monocentric interception. This buffering capacity preserves ecological flows, supports biodiversity, and stabilizes water quality during low-flow periods. Without such decentralized retention mechanisms, baseflow depletion would likely have intensified pollutant concentrations during the dry seasons (see Fig. 6).

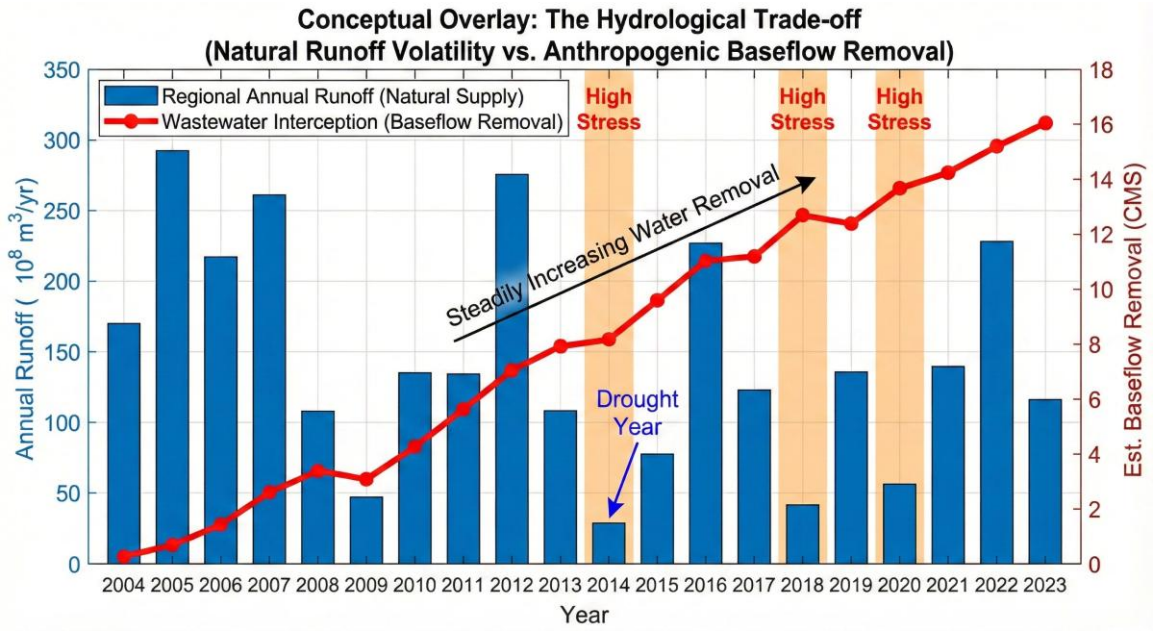


Fig. 6 The Hydrological Trade-off: Natural Runoff Volatility vs. Anthropogenic Baseflow Removal. Blue bars indicate natural annual runoff, while the red line tracks the increasing volume of wastewater intercepted by the centralized sewerage system. As interception increases (reaching ~16 CMS by 2023), less water returns to the river channel, exacerbating baseflow depletion risks during drought years (e.g. 2014 2020). This validates Hypothesis III: Hydrological Recoupling, highlighting the need for wetlands to retain treated water in-stream

Together, these mechanisms illustrate how hybrid infrastructure regimes move urban water systems beyond end-of-pipe control toward integrated socio-hydrological management (Pahl-Wostl et al. 2010). While direct counterfactual observation is not feasible at a basin scale, the convergence of interception trends (Fig. 5) and seasonal concentration risks provides strong inferential support for this mechanism.

4.5 Synthesis: A Unified Framework for Urban Water Resilience

This study integrated distinct lines of evidence into a unified spatio-temporal framework, demonstrating how decentralized Green Infrastructure evolves from a temporary substitute to a permanent ecological backbone. The interrelationship between the four key figures illustrates this trajectory:

4.5.1 Step 1: Structural Deployment (The Hardware): The intervention began with a spatial strategy. Fig. 2 illustrates the Big Dig initiative, establishing a polycentric network of 13 wetland nodes. Unlike centralized wastewater plants (monocentric), this distributed layout provided the necessary redundancy and flexibility to operate within a dense, land-constrained metropolis.

4.5.2 Step 2: Functional Substitution (The Process): During the initial phase (2004–2012), this spatial configuration served a critical temporal function. Fig. 3 captured the Grey Gap phenomenon, quantifying how the wetland network acted as a functional substitute, treating 176,000 CMD of wastewater while the Grey Infrastructure was still under construction. This proves that polycentric Green Infrastructure systems provide immediate safety nets during infrastructure transitions.

4.5.3 Step 3: Evolutionary Adaptation (The Outcome): As the system matured (2013–2024), it exhibited non-linear evolutionary dynamics. Fig. 4 is consistent with a hysteresis-like transition (the full path-dependent loop is shown conceptually in the Graphical Abstract rather than demonstrated by the two-phase comparison), in which the Resilience Index R_e continued to rise despite stabilized pollution loads and reduced maintenance budgets. This indicates that the Green Infrastructure had transitioned into a self-organizing ecosystem, offering resilience benefits that purely engineered (Grey) systems cannot replicate.

4.5.4 Step 4: Spatial Optimization Rules (The Feedback): Finally, to sustain this resilience, governance must adhere to spatial laws. Fig. 5 closes the loop by defining the Ecological Service Radius. The identified 5.8 km disturbance threshold provides the scientific rule for future expansion: to maintain the connectivity of the network and sustain the resilience observed, new green nodes must be spaced within this limit. We emphasize that the 5.8 km figure is a site-calibrated parameter rather than a universal constant: it is the empirically estimated range of the fitted semivariogram for avian indicators in this particular urban matrix, and it would be expected to covary with urban density, the configuration and permeability of the surrounding landscape, and the target taxa. What can be generalized is the method, estimating the variogram range to define a connectivity threshold, whereas the specific distance must be calculated for each basin and indicator.

Together, we defined a comprehensive Plan-Substitute-Adapt-Regulate cycle. This model suggests that urban water resilience is not a static product of engineering, but a dynamic living process that starts with

polycentric placement, relies on functional substitution during transition, gains efficiency through ecological adaptation, and is sustained through scientifically defined spatial connectivity.

4.6. Transforming Constructed Wetlands into Tidal Freshwater Systems: Hydrological Reconnection and Ecological Exchange

Given the dwindling water supply for constructed wetlands, this study proposes a strategic transition from engineered, pump-dependent systems to self-sustaining tidal freshwater wetlands (TFW) by exploiting the tidal regime already present at the site. The core mechanism of this transition is the lowering of the floodplain elevation through flood-control excavation. This transformation aligns with the global recognition of TFWs as critical ecotones that provide disproportionately high ecosystem services relative to their spatial extent (Odum et al. 1984; Whigham et al. 2009). Currently, the high floodplain elevation is approximately 4 meters above the river's deep channel in Dahan Creek's constructed wetlands, isolating the wetland units from the river's natural hydrodynamics. The proposed dredging plan lowers the average ground elevation to approximately -0.05 m (relative to the mean low tide level), effectively placing the wetland surface within the active intertidal zone.

This topographic adjustment facilitates tidal intrusion, allowing the semi-diurnal tides (with an average range of 1.7–2.3 m) to naturally inundate and drain the wetland areas. By reconnecting the floodplain to the river's hydrological pulse, the system shifts from a closed, static water body dependent on artificial inputs to an open, dynamic system driven by natural tidal forces. The proposed design integrates three distinct vertical zones: (1) Subtidal Zones: Deep tidal pools and creeks excavated to -1.0 m to -1.5 m retain water during low tides, providing refugia for fish and aquatic macroinvertebrates. (2) Intertidal Zones: Mudflats and gently sloping banks (graded 1:2.5 to 1:5) are exposed and submerged rhythmically, creating prime foraging grounds for shorebirds and habitats for benthic organisms like crabs and polychaetes. (3) Supratidal Zones: Ecological islands retained at +2.15 m (approx. 0.5 m above mean high tide) preserve existing arboreal vegetation (e.g., *Salix warburgii*), offering roosting sites for arboreal bird species such as the *Lophospiza trivirgata* (Crested Goshawk) and *Psilopogon nuchalis* (Taiwan Barbet).

The restoration of lateral connectivity between the main river channel and the floodplain is the most significant ecological gain of this transition. An improper Green-Grey configuration may lead to wetlands being hydraulically isolated. The new TFW approach may promote a bidirectional exchange, such as: (1) Nutrient Exchange: Tidal flushing facilitates the export of organic carbon and detritus from the highly productive wetland vegetation into the river channel, fueling the aquatic food web. Conversely, river water introduces dissolved oxygen and sediment-bound nutrients into the wetland, preventing stagnation and the anaerobic conditions often observed in aging constructed wetlands. (2) Biological Connectivity: The removal of steep levees and the creation of connecting tidal creeks allow aquatic organisms to migrate freely between the deep channel and the shallow wetland nurseries. This is particularly vital for

the life cycles of estuarine fish and crustaceans recorded in the basin (e.g., *Caridina multidentata* and various Gobiidae), which rely on the interface between lotic and lentic environments.

4.6.1 Designing the Transition to Anticipate Sea-Level Rise

The tidal reconnection described above should be designed in anticipation of sea-level rise (SLR) rather than against a static shoreline. Rising mean sea level extends the tidal prism landward and can itself advance the hydrological reconnection of the floodplain to the estuary; planned with foresight, this lowers the volume of flood-control excavation ultimately required, provided the transition is staged to track, rather than merely react to, the advancing tidal front. The same process, however, threatens a coastal squeeze: where the freshwater tidal zone is pinned against fixed levees and hardened urban edges, the oligohaline band that sustains freshwater treatment and habitat function is progressively compressed as the saline front migrates upstream. Anticipatory governance therefore requires two complementary provisions. First, sufficient upstream accommodation space must be reserved into which the freshwater and oligohaline zones can migrate, preserving their extent as sea level rises. Second, the polycentric cluster should be extended with new nodes at higher upstream elevations, so that as lower-lying wetlands salinize, higher nodes assume the freshwater services and the network as a whole retains its function across the SLR trajectory. Framed this way, SLR becomes a design parameter to be accommodated rather than a hazard to be resisted, consistent with the anticipatory, forecasting orientation that this study advocates.

5. Conclusion

This study provides the results of a rare multi-decade empirical study that demonstrates the long-term value of an NbS approach to manage wastewater in a subtropical megacity. By integrating spatial analysis, longitudinal water-quality trends, infrastructure coupling dynamics, and resilience metrics, we show that Taipei's urban water regime has evolved from a rigid concrete and steel monocentric model toward an adaptive, biologically-based polycentric green model that is coupled with the grey system. Rather than offering a one-size-fits-all solution, this study provides a transferable analytical framework for diagnosing when and how polycentric Green–Grey coupling enhances resilience, particularly in rapidly urbanizing regions facing locked-in and fiscally constrained infrastructure (Frantzeskaki et al. 2019).

Constructed wetlands proved critical at multiple stages of this transition. They a) bridged service gaps during periods of slow centralized deployment, b) enhanced system resilience through functional redundancy, the ability to be flexible and adapt to rapidly changing physical conditions and c) recoupled hydrological processes disrupted by the Grey Infrastructure. These findings challenge the conventional

dichotomy between engineering and ecology, demonstrating that NbS are not auxiliary interventions but essential infrastructural components of sustainable urban water systems.

Limitations and future directions.

The integration realized here is expert-centered, coupling engineering and ecological knowledge with Governance Theory; it does not incorporate the structured participation of non-technical stakeholders (residents, recreational users and community groups) that characterizes fully transdisciplinary, co-produced sustainability research (Lang et al. 2012). Although such actors are present in the system (e.g., recreational use of the Happy Waterfront corridor and public support for the wetlands), their preferences and local knowledge were not formally elicited or embedded in the analytical framework. Extending this infrastructure-centered model toward genuine knowledge co-production is therefore a priority for future work.

More broadly, under projected population growth and sea-level rise through 2100, water availability, not water quality alone, will increasingly constrain megacity viability, make in-basin retention and reuse a first-principles a necessity rather than an amenity (Lobato de Magalhães and Otte 2023).

In the context of accelerating climate uncertainty and urban densification, this study provides robust empirical support for Ostrom's central insight that resilience in complex urban systems (Folke 2006) arises from institutional diversity, infrastructural hybridity, and polycentric governance. We advance polycentric governance theory by operationalizing it as a measurable property of hybrid infrastructure systems, rather than treating it solely as an abstract institutional arrangement. By explicitly linking governance principles to temporal system performance, functional redundancy, and spatial ecological buffering, this study transforms polycentricity from a normative governance ideal into an empirically testable analytical framework. In doing so, we respond directly to longstanding critiques of theoretical vagueness (Thiel et al. 2019) and demonstrate how governance diversity is materially instantiated through infrastructure design and socio-ecological processes.

6. Governance Implications: Advancing Urban Resilience through Polycentric and Hybrid Infrastructure Governance

Consistent with the urban resilience frameworks advanced by UN-Habitat and the OECD, this study argues for treating urban water infrastructure as an evolving socio-technical system rather than a static engineering asset. Translating our empirical findings into actionable strategies requires governance approaches that emphasize adaptability, multi-level coordination, and long-term system capacity building (OECD 2020).

6.1 Mainstreaming Hybrid Infrastructure within Polycentric Governance Systems

In line with UN-Habitat's call for integrated and multi-scalar urban governance, urban water planning would be wise to institutionalize a Green–Grey coupling approach as a core component of resilient infrastructure systems. Rather than treating NbS as peripheral or experimental interventions, constructed wetlands should be formally recognized as permanent infrastructural nodes within polycentric governance arrangements. This necessitates coordinated decision-making and a good understanding of the function and benefits of constructed wetlands across water utilities, environmental authorities, and urban planning agencies to mobilize diverse capacities and respond more effectively to uncertainty and systemic shocks (Kabisch et al. 2016).

6.2 Aligning Financial Instruments with Long-Term Resilience Objectives

Echoing the OECD recommendations on resilience-oriented public investment, NbS should be treated as long-term capital assets whose value lies in sustained system performance and reliability rather than trendy short-term efficiency gains. Financing mechanisms should therefore move beyond project-based funding toward stable, lifecycle-oriented instruments, including integration into water tariff structures, ecosystem service payment schemes, and innovative green finance tools such as resilience bonds. These mechanisms help insulate NbS from fiscal volatility and ensure continuity of function under changing climatic and economic conditions (Droste et al. 2017).

6.3 Deploying NbS to Restore Urban Hydrological Connectivity

UN-Habitat emphasizes the restoration of urban ecological processes as a precondition for climate-resilient cities. In metropolitan contexts where centralized sewerage systems have disrupted natural hydrological cycles and reduced river baseflow, NbS can be strategically deployed to provide both tertiary treatment and hydrological buffering. By retaining and treating water within river corridors, wetlands contribute to the restoration of ecological flows, enhance seasonal dilution capacity, and mitigate the unintended externalities associated with end-of-pipe wastewater diversion (Golden and Hoghooghi 2018).

6.4 Cultural Ecosystem Services as a Source of Social and Institutional Resilience

Consistent with the OECD's recognition of social capital as a critical dimension of resilience, wetlands embedded in dense urban environments earn their place through cultural ecosystem services as much as through treatment performance. Recreation, urban cooling, human well-being, and environmental education enhance community engagement and public trust, reinforcing the social foundations necessary for sustained governance capacity and long-term infrastructure legitimacy (Andersson et al. 2014).

6.5 Shifting from Compliance-Based Regulation to Resilience-Based Performance Evaluation

Both the UN-Habitat and OECD advocate moving beyond static compliance metrics toward adaptive performance assessment. Regulatory frameworks governing urban water systems should therefore incorporate resilience-based indicators that capture temporal stability and adaptive capacity, such as the temporal stability index (R_e) applied in this study. Evaluating infrastructure through its ability to maintain function under disturbance provides a more robust basis for decision-making in an era of climate uncertainty and rapid urban transformation (Linkov et al. 2014).

Supplementary Information: Supplementary data are provided as Online Resources. The data file (Online Resource 2 (ESM_2.xlsx)) contains the station-year water-quality records underlying Fig. 3 (sheet S1), the phase-level statistics underlying Fig. 4 and Table 2 (sheet S2), the sewerage connection series (sheet S3), the annual runoff series underlying Fig. 6 (sheet S4), and the monitoring station inventory (sheet S5).

Author Contributions: The manuscript was conceptualized by Wei Ta Fang, Shang-Shu Shih, and Bai-You Cheng. Wei Ta Fang, Shang Shu Shih, and Annapurna Sharma developed the methodology and the formal analyses were performed by Wei Ta Fang, Shang-Shu Shih, Bai-You Cheng, and Annapurna Sharma. Bai-You Cheng and Wei Ta Fang visualized the project and the data were curated by: Wei Ta Fang, Shang-Shu Shih, and Bai-You Cheng. Ben LePage and Wei Ta Fang developed the first draft of the manuscript. Wei Ta Fang, Shang Shu Shih, Bai-You Cheng, Annapurna, Sharma, and Ben LePage reviewed. Edited, and prepared the final version of the manuscript. Supervision was performed by Wei Ta Fang and Ben LePage.

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***Ben LePage's** research interests are broad, ranging from reconstructing ancient terrestrial ecosystems, Global Climate Change, Environmental Justice, Philosophy of Science, and Sustainability. His experience in the academic and industrial sectors allowed him develop and implement a transdisciplinary cross-cutting approach for solving and cleaning legacy environmental issues and develop solutions for the imminent environmental and food and water security issues that global change will drive. He was a Distinguished Visiting Chair Professor in the Institute of Sustainability Management and Environmental Education at NTNU in Taipei where his pedagogy focused on conducting sound science using a transdisciplinary approach to solve real-world problems. He has served on several boards and was a former President of the Society of Wetland Scientists (SWS) and President of the SWS Professional Certification Program. His work and that of his students and co-authors have been published in several highly respected, international peer-reviewed journals.

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Data Availability: All of the data supporting the findings of this study are provided in the Supplementary Material. The underlying records are Taiwan open-government data and include: river water-quality monitoring records from the Ministry of Environment, sewerage connection statistics from the Construction and Planning Agency of the Ministry of the Interior, and runoff records from the Water Resources Agency of the Ministry of Economic Affairs.

Declarations

Competing Interests: 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.

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References

Ahern J (2011) From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. Landsc Urban Plan 100:341-343

Andersson E, Barthel S, Borgström S, Colding J, Elmqvist T, Folke C, Gren Å (2014) Reconnecting cities to the biosphere: Stewardship of green infrastructure and urban ecosystem services. Ambio 43:445-453

Anselin L (1995) Local indicators of spatial association—LISA. Geogr Anal 27:93-115. https://doi.org/10.1111/j.1538-4632.1995.tb00338.x

Anselin L (2019) A local indicator of multivariate spatial association: Extending Geary's c. Geogr Anal

902 51:133-150
903 Bakhshipour AE, Khaksar M, Valerdi R, Ditmars J (2019) Optimization of hybrid green-blue-gray
904 stormwater infrastructure for life cycle cost and resilience. Sustain Cities Soc 47:101490.
905 https://doi.org/10.1016/j.scs.2019.101490
906 Callaghan CT, Major RE, Cornwell WK, Poore AG, Wilshire JH, Lyons MB (2021) A global analysis of
907 wild bird–urbanization relationships reveal a broad negative impact. Nature Comm. 12:1-10
908 Carlisle K, Gruby RL (2019) Polycentric systems of governance: A theoretical model for the commons.
909 Policy Studies Journal 47:927-952
910 Chang Y-H, Wu C-H, Yuan C-S (2018) Spatial and temporal analysis of river water quality in a highly
911 industrialized river basin in Taiwan. Environmental Monitoring and Assessment 190:685
912 Cheng BY, Liu TC, Shyu GS, Chang TK, Fang WT (2011) Analysis of trends in water quality:
913 Constructed wetlands in metropolitan Taipei. Water Sci Technol 64:2143-2150
914 Cumming GS (2011) Spatial resilience: Integrating landscape ecology, resilience, and sustainability.
915 Landsc Ecol 26:899-911
916 Depietri Y, McPhearson T (2017) Changing urban risk: 150 years of climatic hazards in New York City.
917 Climatic Change 148:95-108
918 Donohue I, Hillebrand H, Montoya JM, Petchey OL, Pimm SL, Fowler MS, Yang Q (2016) Navigating
919 the complexity of ecological stability. Ecology Letters 19:1172-1185
920 Donohue I, Petchey OL, Montoya JM, Jackson AL, McNally L, Viana M, Yang Q (2013) On the
921 dimensionality of ecological stability. Ecology Letters 16:421-429
922 Droste N, Schröter-Schlaack C, Hansjürgens B, Zimmermann H (2017) Implementing nature-based
923 solutions in urban areas: Financing and governance aspects. In N. Kabisch, H. Korn, J. Stadler, &
924 A. Bonn (eds), Nature-based solutions to climate change adaptation in urban areas (pp. 307–321).
925 Springer
926 Fan P, Xu L, Yue W, Chen J (2023) Accessibility of public urban green space in an urban periphery: The
927 case of Shanghai. Sustain Cities Soc 91:104445. https://doi.org/10.1016/j.scs.2023.104445
928 Filazzola A, Shrestha N, MacIvor JS (2019) The contribution of constructed green infrastructure to urban
929 biodiversity: A synthesis and meta-analysis. Journal of Applied Ecology 56:2131-2143
930 Folke C (2006) Resilience: The emergence of a perspective for social–ecological systems analyses. Glob
931 Environ Change 16:253-267. https://doi.org/10.1016/j.gloenvcha.2006.04.002
932 Folke C, Biggs R, Norström AV, Reyers B, Rockström J (2016) Social-ecological resilience and
933 biosphere-based sustainability science. Ecology and Society, 21(3)
934 Folke C, Carpenter S, Walker B, Scheffer M, Elmqvist T, Gunderson L, Holling CS (2004) Regime shifts,
935 resilience, and biodiversity in ecosystem management. Annual Review of Ecology, Evolution, and
936 Systematics 35:557-581

Frantzeskaki N (2019) Seven lessons for planning nature-based solutions in cities. Sustain Cities Soc 46:101415

Frantzeskaki N, McPhearson T, Collier MJ, Kendal D, Bulkeley H, Dumitru A, Pintér L (2019) Nature-based solutions for urban climate change adaptation: Linking science, policy, and practice communities for evidence-based decision-making. BioScience 69:455-466

Ganjirad M, Delavar MR, Bagheri H, Azizi MM (2025) Optimizing urban critical green space development using machine learning. Sustain Cities Soc 120:106158

Geels FW (2011) The multi-level perspective on sustainability transitions: Responses to seven criticisms. Environmental Innovation and Societal Transitions 1:24-40

Golden HE, Hoghooghi N (2018) Green infrastructure and its catchment-scale effects: An emerging science. WIREs Water 5: e1254. https://doi.org/10.1002/wat2.1254

Haase D, Larondelle N, Andersson E, Artmann M, Borgström S, Breuste J, … Elmqvist T (2014) A quantitative review of urban ecosystem service assessments: Concepts, models, and implementation. Ambio 43:413-433. https://doi.org/10.1007/s13280-014-0504-0

Hashimoto T, Stedinger JR, Loucks DP (1982) Reliability, resilience, and vulnerability criteria for water resource system performance evaluation. Water Resour Res 18:14-20

Holling CS (1973) Resilience and stability of ecological systems. Annu Rev Ecol Syst 4:1-23

Huang J-C, Lin C-C, Chan S-C, Lee T-Y, Hsu S-C, Lee L-C, Lin W-C (2012) Stream discharge characteristics through urbanization gradient in Danshui River, Taiwan: Perspectives from observation and simulation. Environmental Monitoring and Assessment 184:5689-5703

Hunter C (1998) Perceptions of the sustainable city and implications for fresh water resources management. International Journal of Environment and Pollution 10:84-103

Kabisch N, Frantzeskaki N, Pauleit S, Naumann S, Davis M, Artmann M, Bonn A (2016) Nature-based solutions to climate change mitigation and adaptation in urban areas: Perspectives on indicators, knowledge gaps, barriers, and opportunities for action. Ecol Soc 21:39

Kabisch N, Korn H, Stadler J, Bonn A (eds) (2017) Nature-based solutions to climate change adaptation in urban areas: Linkages between science, policy and practice. Springer Open

Kadlec RH, Wallace S (2008) Treatment wetlands (2nd ed.). CRC Press

Kong F, Yin H, Nakagoshi N, Zong Y (2010) Urban green space network development for biodiversity conservation: Identification based on graph theory and gravity modeling. Landsc Urban Plan 95:16-27

Lang DJ, Wiek A, Bergmann M, Stauffacher M, Martens P, Moll P, Swilling M, Thomas CJ (2012) Transdisciplinary research in sustainability science: Practice, principles, and challenges. Sustainability Science, 7(S1), 25–43. https://doi.org/10.1007/s11625-011-0149-x

Larsen TA, Hoffmann S, Lüthi C, Truffer B, Maurer M (2016) Emerging solutions to the water challenges

of an urbanizing world. Science 352:928-933

Li X, Zhou W, Ouyang Z (2020) Forty years of urban green infrastructure research: Benefits, multifunctionality, and sustainability. Sustain Cities Soc 60:102263

Linkov I, Bridges T, Creutzig F, Decker J, Fox-Lent C, Kröger W, … Thiel-Clemen T (2014) Changing the resilience paradigm. Nature Climate Change 4:407-409. https://doi.org/10.1038/nclimate2227

Linton J, Budds J (2014) The hydrosocial cycle: Defining and mobilizing a relational-dialectical approach to water. Geoforum 57:170-180. https://doi.org/10.1016/j.geoforum.2013.10.008

Liou S-M, Lo S-L, Wang S-H (2004) A generalized water quality index for Taiwan. Environmental Monitoring and Assessment 96:35-52. https://doi.org/10.1023/B:EMAS.0000031715.83752.a1

Lobato de Magalhães T, Otte ML (eds) (2023) Wetlands for remediation in the tropics. Springer. https://doi.org/10.1007/978-3-031-23665-5

Masi F, Rizzo A, Regelsberger M (2018) The role of constructed wetlands in a new circular economy, resource recovery, and wastewater treatment framework. Resources 7:25

Meerow S, Newell JP, Stults M (2016) Defining urban resilience: A review. Landsc Urban Plan 147:38-49

Mitchell MG, Suarez-Castro AF, Martinez-Harms M, Maron M, McAlpine C, Gaston KJ, Rhodes JR (2015) Reframing landscape fragmentation's effects on ecosystem services. Trends in Ecology and Evolution 30:190-198

Morrison TH, Adger WN, Brown K, Lemos MC, Huitema D, Hurlbert M (2019) The black box of power in polycentric environmental governance. Glob Environ Change 57:101934

Nakai F, Kito S, Okubo K (2025) Spatial optimisation for managed retreat and nature-based solutions in climate adaptation. Sustain Cities Soc 124:106246

Odum WE, Smith III TJ, Hoover JK, McIvor CC (1984) The ecology of tidal freshwater marshes of the United States east coast: A community profile. US Fish and Wildlife Service, FWS/OBS-83/17

OECD. (2020) Nature-based solutions for adapting to water-related climate risks (OECD Environment Policy Paper No. 21). OECD Publishing. https://doi.org/10.1787/2257873d-en

Oral HV, Carvalho P, Gajewska M, Ursino N, Masi F, van Hullebusch ED, Rizzo A (2020) A review of nature-based solutions for urban water management in European circular cities: A critical assessment based on case studies and literature. Blue-Green Systems 2:112-136

Ostrom E (2010) Beyond markets and states: Polycentric governance of complex economic systems. American Economic Review 100:641-672

Otto B, Schleifer L (2020) Domestic water use grew 600% over the past 50 years. World Resources Institute. Insights, February 11, 2020. https://www.wri.org/insights/domestic-water-use-grew-600-over-past-50-years

Pahl-Wostl C (2019) The role of governance modes and meta-governance in the transformation towards sustainable water governance. Environmental Science and Policy 91:6-16

Pahl-Wostl C, Holtz G, Kastens B, Knieper C (2010) Analyzing complex water governance regimes: The Management and Transition Framework. Environmental Science and Policy 13:571-581

Pimm SL (1984) The complexity and stability of ecosystems. Nature 307:321-326

Public Works Department, New Taipei City Government. (2024) Sewerage connection statistics report. (in Chinese)

Scheffer M, Carpenter S, Foley JA, Folke C, Walker B (2001) Catastrophic shifts in ecosystems. Nature 413:591-596

Strohbach MW, Haase D, Kabisch N (2019) Birds and the city: Urban biodiversity, land use, and socio-economics. Sci Total Environ 693:133451

Thiel A, Blomquist WA, Garrick DE (2019) Governing complexity: Analyzing and applying polycentricity. Cambridge University Press

Tilman D (1996) Biodiversity: Population versus ecosystem stability. Ecology 77:350-363

Tritinger AS, Hubbard ZN, Chambers CE, Suedel BC, Bourne EM, Moynihan EB, Mohan RK, King JK (2024) Engineering with Nature: An Atlas, Volume 3 (ERDC SR-24-2). U.S. Army Engineer Research and Development Center. https://doi.org/10.21079/11681/48453

Vymazal J (2010) Constructed wetlands for wastewater treatment. Water 2:530-549

Walsh CJ, Fletcher TD, Burns MJ (2012) Urban stormwater runoff: A new class of environmental flow problem. PLoS One 7: e45814. https://doi.org/10.1371/journal.pone.0045814

Wang YB, Liu CW, Liao PY, Lee JJ (2018) Spatial pattern assessment of river water quality: Implications of non-point source pollution in the Kaoping River basin, Taiwan. Environmental Monitoring and Assessment 190:1-16

Whigham DF, Verhoeven JT, Samarkin V, Megonigal PJ (2009) Responses of Avicennia germinans (black mangrove) and the soil microbial community to nitrogen addition in a hypersaline wetland. Estuaries and Coasts 32:926-936

Wong THF, Brown RR (2009) The water sensitive city: Principles for practice. Water Sci Technol 60:673-682. https://doi.org/10.2166/wst.2009.436

Xue B, Geng Y, Mitchell PD, Ren W (2015) Opacity of decoupling: A technical note. Ecol Indic 48:235-238

Wooldridge JM (2010) Econometric analysis of cross section and panel data, 2nd edn. MIT Press, Cambridge

Zeng Y, Shih S-S, Fang W-T (2020) Impact of hydrological fluctuations on water quality resilience in a subtropical urban river. Water 12:2450

Zuniga-Teran AA, Staddon C, de Vito L, Gerlak AK, Ward S, Schoeman Y, Booth G (2020) Challenges of mainstreaming green infrastructure in built environment professions. Sustain Cities Soc 53:101893. https://doi.org/10.1016/j.scs.2019.101893

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