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GIS-Based Construction Management Framework for Sponge City Infrastructure: A Comparative Study for Xiamen and Izmir

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ABSTRACT

This research presents a Geographic Information System-based Construction Management Framework (GIS-CMF) for sponge city infrastructure under ecological and spatial constraints, applied comparatively to İzmir (Türkiye) and Xiamen (China). United States Environmental Protection Agency Storm Water Management Model Software (EPA SWMM 5.2.4) simulations (Nash–Sutcliffe Efficiency-NSE = 0.71–0.78) project a model-suggested potential improvement in the range of 15–25 percentage points in Annual Runoff Volume Capture Ratio for three İzmir pilot catchments, subject to field validation. Spatial autocorrelation analysis confirms statistically significant impermeable surface clusters. Institutional comparison through learning curve and barrier analysis explains implementation velocity differences without direct statistical equivalence claims. Eight transferable GIS-CMF principles are derived for construction project managers across contrasting institutional and geographical contexts.

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1. INTRODUCTION

Urban flooding is one of the most economically damaging natural hazards that cities face today and its impacts are growing due to climate change. Climate change is transforming precipitation patterns in the form of more intense events, longer dry spells and in many areas an unsettling combination of both at once. Under Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6) projections, Mediterranean cities face a dual challenge: higher-intensity short-duration rainfall under both SSP2-4.5 and SSP5-8.5 (Shared Socioeconomic Pathways; SSP2-4.5 represents an intermediate emissions scenario, SSP5-8.5 a high-end fossil-fuel-driven pathway), combined with increasing seasonal drought, compressing the effective window for stormwater management intervention [1]. Concurrently, accelerated urban development persists in superseding infiltration-capable substrates with impermeable layers, thereby exacerbating surface discharge, whilst stormwater conveyance systems lag in maintaining parity [2].

Against these new circumstances, nature-based infrastructure and especially sponge city design has emerged as an innovative alternative to purely grey-infrastructure approaches. The "Sponge City" concept, introduced by Prof. Kongjian Yu and formalized in Chinese national policy in 2013–2014, coordinated by the Ministry of Housing and Urban-Rural Development (MOHURD), represents one of the most ambitious government-led urban water management programme in history [3]. China targets 80% of urban areas to capture and reuse at least 70% of annual rainfall through a combination of green roofs, rain gardens, permeable pavements, bioswalesa nd restored wetlands by 2030 [4]. Türkiye has commenced moving in a similar direction. For instance, İzmir Metropolitan Municipality launched the "Sünger Kent İzmir" programme in late 2022, aiming a five-year transformation of the city's stormwater paradigm [5]. The coastal cities of Antalya and Kocaeli have also initiated comparable green infrastructure investments, reflecting a developing national trend that has yet to find its unifying policy concept [6].

Although sponge city hydrology and policy charm greater interest, a significant gap still remains in the literature for practitioners in the construction industry. Since the integration of GIS-based spatial analysis with construction project management (CPM) theory in the context of sponge city implementation remains largely unexplored (especially from the view of a comparative and cross-national aspects), this gap creates practical issues that city administrators and construction project managers need. By establishing frameworks that can translate spatial data from maps into planning/scheduling decisions, budget estimation and quality targets will diminish this gap. This study tries to provide four contributions by aiming to close this gap. Firstly, a transparent, reproducible GIS-CMF for sponge city infrastructure under ecological and spatial constraints is developed and described with full methodological specification. Secondly, the framework is applied comparatively to İzmir and Xiamen (China) two coastal cities at very different stages of sponge city maturity by supported by a secondary Turkish reference case (Antalya). Thirdly, hydrological performance projections are grounded in EPA SWMM simulations and IPCC AR6 climate scenarios and finally eight transferable GIS-CMF principles are deduced for construction project managers.

Authors firstly review related literature in Section 2 and give details the methodology with full reproducibility specifications in Section 3. Sections 4 and 5 provide city profiles and spatial analysis results. Developed GIS-CMF is mentioned in Section 6 and subsequently Section 7 performs the comparative institutional analysis and Section 8 derives transferable principles for practitioners. Sections 9 and 10 present discussion and conclusions.

1.1. Research Questions

Building on the gaps identified above, this study is organized around four research questions:

RQ1: How do spatial-ecological constraints such as ecological red lines, slope thresholds, and groundwater depth change the prioritization of sponge city intervention sites in Mediterranean versus subtropical coastal urban settings?

RQ2: What magnitude of Annual Runoff Volume Capture Ratio (AVCR) improvement is realistically achievable under İzmir's Mediterranean conditions given current low-impact development (LID) configurations and how do these projections compare with Xiamen's measured outcomes?

RQ3: Which institutional barriers most strongly explain the implementation velocity differences between Türkiye's municipal-initiated and China's nationally mandated sponge city programmes and how can learning curve theory be implemented to project İzmir's trajectory?

RQ4: What transferable GIS-CMF principles can be derived from the İzmir–Xiamen comparison that remain applicable across contrasting institutional and geographical contexts including cities without an established national sponge city policy?

These research questions are discussed in different sections: RQ1 is discussed in Sections 5.1 and 5.3; RQ2 in Sections 5.2 and 6.1-6.2; RQ3 in Section 7; RQ4 in Section 8. Each answer is treated as a structured proposition grounded in spatial, hydrological as well as institutional evidence with explicitly stated uncertainty bounds rather than overconfident conclusions.

2. LITERATURE REVIEW

2.1. Sponge City as a Construction Management Challenge

The sponge city concept integrates low-impact development (LID) measures such as bio-retention cells, sunken green spaces, permeable pavements, and green roofs into both existing and new urban fabric [7]. Unlike conventional grey infrastructure, these nature-based solutions impose distinct construction management challenges: interdisciplinary coordination across landscape architecture, hydraulic engineering, and urban planning; non-standard procurement for specialized ecological materials; iterative performance monitoring rather than fixed completion criteria; and sensitivity to ecological constraints during construction [8].

Construction management literature has examined widely the cost overruns in green infrastructure projects [9], lifecycle cost analysis of LID measures [10] and quality key performance indicators for stormwater performance [11]. However, these studies have a tendency to deal with sponge city construction as an engineering problem rather than a holistic project management application. The present study situates sponge city construction within the PMBOK framework [12], examining how the five process groups are adapted under ecological and spatial constraints. Recent meta-analyses confirm that PMBOK-aligned frameworks applied to nature-based infrastructure improve schedule adherence by 18–24% compared to unstructured approaches, primarily by formalizing the ecological window constraint as a planning input [13].

2.2. GIS Applications in Urban Infrastructure Management

GIS provides the spatial analytical backbone for sponge city planning, enabling delineation of hydrological catchments, identification of ecologically sensitive zones, runoff simulation, and project site suitability analysis [14]. Studies in Xiamen have employed GIS-based hydrological analysis to extract flow paths, divide sub-catchments, and model LID performance at the block scale [15]. The integration of remote sensing with GIS enables near-real-time monitoring of drainage systems, supporting emergency response for rainfall disasters [16].

In the construction management context, GIS supports spatial scheduling — the allocation of construction resources across geographically distributed project sites — which is particularly relevant for city-scale sponge infrastructure involving hundreds of simultaneously managed sub-projects [17]. A GIS-based governance platform integrating multi-source spatial data has been demonstrated for construction oversight in Xiamen, showing scalability for spatiotemporal urban management [18]. More recently, Liang et al proposed a Sponge City+ parametric toolkit combining GIS-based constraint mapping with automated LID dimensioning, reporting a roughly 35% reduction in design iteration time [19].

Spatial autocorrelation methods — notably Moran's I and Local Indicators of Spatial Association (LISA) — have been applied to urban impervious surface distributions to identify statistically significant hotspots and assess spatial non-stationarity in runoff generation [20]. These methods are now considered standard in hydrological GIS analysis and are adopted in the present study to move beyond descriptive mapping toward confirmatory spatial statistics.

2.3. Urban Resilience Concept under Climate Change Scenarios

Urban resilience, or in particular infrastructure resilience comprises both the capacity to withstand shocks and to recover and adapt [21]. Dynamic resilience frameworks extend static assessments by modelling how resilience evolves under changing climate forcings, which is essential for sponge city design horizons of 20–30 years [22]. Under IPCC AR6

SSP2-4.5, Mediterranean cities including İzmir are projected to experience a 15–30% increase in 1-in-10-year hourly rainfall intensities by 2050, while mean annual precipitation is projected to decline by 12–18%, creating a compound risk profile that complicates design-storm selection [1]. SSP5-8.5 projections roughly double these anomalies. These divergent trends mean that AVCR targets calibrated to historical rainfall may need upward revision within the near-term planning horizon [23].

Sponge city implementation is further shaped by ecological red lines — regulatory spatial boundaries protecting biodiversity, water resources, and green coverage — as well as geomorphological factors and land use regulations [24]. The comparative literature on urban resilience between China and Türkiye is growing [25, 26]. Xiamen is consistently cited among the most successful Chinese sponge city implementations [26], and systematic comparison with emerging programmes yields both theoretical and practical value for construction management scholars and practitioners.

2.4. Institutional Learning Curves and Barrier Analysis

When programmes differ in scale by an order of magnitude such as Xiamen's 236-project portfolio versus İzmir's 8-10 planned and initiated pilots, direct statistical comparison of implementation speed is methodologically inappropriate [27]. Learning curve theory was first developed for manufacturing and has since been applied to construction programmes to characterise efficiency gains as cumulative experience accumulates [28]. Barrier analysis, rooted in institutional economics, identifies the structural impediments — such as regulatory frameworks, financing instruments, contractor capability, and professional norms — that constrain programme velocity independently of technical strength [29]. Section 7 discusses and provides application for both concepts to interpret contrast between İzmir and Xiamen from the point of institutional points without overgeneralizing equivalence.

3. RESEARCH METHODOLOGY

3.1. Comparative Case Study Design

This study provides a comparative case study methodology [30], selecting İzmir (Türkiye) and Xiamen (China) as primary paired cases based on four criteria. Firstly, (1) coastal city morphology with comparable hydrological vulnerability, secondly active sponge city programmes being conducting in both cities, thirdly the availability of open spatial and project data for the research and finally contrasting institutional contexts representing emerging versus mature programme stages. In addition Antalya (Türkiye) is introduced as a secondary reference case to partially examine the single-country limitation and to support the institutional barrier analysis discussed in Sections 4.3 and 7.3. The comparative design enables identification of context-specific versus transferable construction management principles.

3.2. GIS-Based Spatial Analysis Protocol

Spatial analysis was conducted in QGIS 3.34 LTR using the SAGA 9.3.2 provider. The analytical protocol comprises the following five steps:

(1) Watershed delineation from SRTM 30 m DEM using SAGA's "Watershed Basins" algorithm (8-direction flow routing); fill-sink preprocessing with Wang & Liu (2006) algorithm.

(2) Impervious surface extraction from Copernicus Urban Atlas 2018 (İzmir) and CLUD 2020 (Xiamen) by reclassification to binary impervious/pervious, validated against Sentinel-2 NDVI (10 m, 2023 composite) with overall accuracy ≥92%.

(3) Ecological constraint overlay: vector union of red line shapefiles with project site polygons to classify each site as (a) within red line, (b) within 50-m buffer, or (c) unconstrained.

(4) CN assignment following USDA-NRCS TR-55 (2004) look-up tables adapted for Mediterranean and subtropical conditions per Boughton (1989); hydrological soil group mapping from FAO Harmonised World Soil Database v.1.2.

(5) Spatial autocorrelation of impervious surface (500 m raster grid) computed using Moran's I in PySAL 2.9 (DOI: 10.5281/zenodo.11149516); z-score significance at $\alpha = 0.05$ with 999 permutations under the conditional randomization assumption.

3.3. SWMM-Based Hydrological Performance Simulation

In the absence of long-term field monitoring data for İzmir pilot catchments — an acknowledged limitation at this stage of the programme — EPA SWMM 5.2.4 is used to provide model-based estimates of pre-LID and post-LID AVCR and peak flow reduction. This follows the validated methodology of Xu et al. (2017) [31], who demonstrated SWMM's suitability for block-scale LID-BMP planning in Chinese sponge city contexts. The SWMM model for İzmir was established for three illustrative sub-basins: Buca Fırat (28 ha, 74% impervious cover), Karşıyaka Pilot Zone (19 ha, 71%) and Buca 138th Street Corridor (4.2 ha, 83%). Sub-catchment delineation, routing parameters and inlet geometry are obtained from İZSU drainage network data and field surveys reported in the İZSU Technical Report (2023) [32].

Calibration of runoff coefficients against observed peak flow data from the İZSU 2019–2023 flood report yields a Nash-Sutcliffe Efficiency (NSE) of 0.71–0.78 and a Percentage Bias (PBIAS) of ±8–12% for the three sub-catchments in pre-LID configuration — acceptable for planning-level analysis, though below the 0.80 NSE threshold recommended for design-level applications. Model uncertainty is quantified through a Monte Carlo sensitivity analysis ($n = 500$; Latin Hypercube Sampling) varying impervious cover ±5%, Manning's roughness ±20%, and LID area ratio ±15%. Results are reported as mean ± one standard deviation. Because the pre-LID calibration NSE values (0.71–0.78) fall below the 0.80 threshold recommended for design-level SWMM applications (Moriasi et al., 2007 [ref]), all AVCR and peak flow projections in this study are explicitly designated as planning-level model estimates, not design-level predictions. A prospective statistical validation plan is embedded in the GIS-CMF as a mandatory programme deliverable: upon completion of the 2025–2026 field monitoring cycles at the three İzmir pilot sub-catchments, observed and simulated monthly runoff volumes will be compared using three complementary metrics — (i) Nash-Sutcliffe Efficiency (NSE), with an improvement target of ≥0.80 for post-LID conditions; (ii) Kling-Gupta Efficiency (KGE), targeting ≥0.75, which jointly evaluates correlation, bias, and variability components and is less sensitive to peak-flow bias than NSE alone (Gupta et al., 2009 [ref]); and (iii) Root Mean Square Error normalised to the observed standard deviation (RSR), targeting ≤0.60. If post-construction monitoring yields NSE < 0.70 for any sub-catchments, the SWMM model should be reparameterised using as-built LID geometry before any Phase 2 sites are designed. We recommend that this validation protocol should be adopted (and stipulated in the contract a proper way) as a contractual milestone in the project brief for each pilot site.

3.4. GIS-CMF Development

For the development of a GIS-CMF, PMBOK [12] standards and the sponge city lifecycle literature are used [33] and four analytical dimensions were synthesised. They are

-Spatial Planning and Site Suitability,

-Preliminary Cost Feasibility,

-Schedule Management,

-Quality Management.

Each dimension is evaluated comparatively for İzmir and Xiamen utilizing a standardised scoring rubric.

4. CITY PROFILES AND SPONGE CITY INITIATIVES

4.1. İzmir, Türkiye

İzmir is Türkiye's third-largest city and has a metropolitan population of nearly 4.4 million (TÜİK, 2023). The geography of the city can be expressed as the head of İzmir Bay on the Aegean coast, bounded by steep hillsides that funnel stormwater runoff toward a flat coastal plain which is a topography that has historically concentrated flood risk in its densest urban districts. Between 2019 and 2023, the city recorded over 5,000 flood incidents linked to stormwater [32]. According to IPCC AR6 SSP2-4.5, İzmir is projected to face 8-12 additional extreme precipitation in other words events exceeding 20 mm/day days per year by 2050. However, mean annual precipitation is simultaneously projected to decline by 12 to 18%. This compound risk profile that is more intense events, less water overall, complicates conventional design-storm selection and makes the case for adaptive, modular infrastructure particularly strong [1].

İzmir Metropolitan Municipal Council in October 2022 adopted Türkiye's first sponge city regulation under the title of "Sünger Kent İzmir" programme and it was formally put in force in the same year. The programme aims full sponge city status within five years by employing nature-based measures: rainwater harvesting, rain gardens, permeable pavements, bioswales, infiltration ponds and ecological ponds. In this context, key pilot projects include Buca Fırat Nursery Park, Kardeşenler Kindergarten, Buca Betontas Marketplace, Buca 138th Street, five ESHOT bus stops with 500-litre collection tanks and Meles and Manda Watershed Management Projects [34]. The city also participates in the EU CLIMAAX project through the CRIZ-ERS resilience strategy initiative [35].

4.2. Xiamen, China

Xiamen is a coastal city in Fujian Province with a population of 5.2 million approximately according to (Xiamen Bureau of Statistics, 2023. The city records nearly 1,200 mm of annual precipitation concentrated in the typhoon season from May to October [36]. Xiamen has developed 236 sponge city projects with total investment exceeding 7.2 billion RMB (approximately USD 1 billion), covering around 19 km² by 2020 [37], since it was elected in 2015 as one of China's first 16 national Sponge City Construction pilot cities [4],

Different programme characteristics comprise integration of coastal ecology management with urban water infrastructure, the Yangfang residential area redevelopment as a model sponge community and a GIS-based governance platform for construction monitoring [18]. The resilience of programme was tested in practice when reconstructed sponge areas withstood Typhoon Nepartak (2016) without soil saturation [37]. Nevertheless, critics have pointed that excessive focun on non-integrated green infrastructure has left some Xiamen sub-catchments still susceptible to flooding during extreme events exceeding the 20-year return period [38].

4.3. Antalya, Türkiye-Auxiliary/Reference Case

Antalya, with a metropolitan population of approximately 2.6 million (TÜİK, 2023), encounters similar Mediterranean climate risk profile to İzmir but not adopted a formal sponge city regulatory framework, is utilized as a secondary Turkish reference case to partially examine the single-country limitation in the institutional analysis. The Antalya Metropolitan Municipality commenced green infrastructure projects under the LIFE-IP ClimAction Antalya programme (EU LIFE, 2022–2026) [39] such as the pilot permeable pavement installation on Şarampol Street (Muratpaşa district, 2021). It succeeded at the site level but was not replicated in subsequent projects due to lack of standard specification or procurement clause required it in public procurement contracts. This fact underlines that just defining characteristic of green infrastructure investment without regulatory architecture will result in failure and the contrast with İzmir's regulation-first approach provides the robust available proof for the centrality of regulatory design in programme sustainability.

5. GIS-BASED COMPARATIVE SPATIAL ANALYSIS

5.1. Hydrological Constraint Mapping

For İzmir, our model, namely GIS-based Digital Elevation Model (DEM), analysis for İzmir detects three certain hydrological constraint zones; (i) Meles River catchment with the characteristics of western urban core, high flood risk and low infiltration potential due to dense impervious cover; (ii) Manda River catchment which is characterised as northern districts, moderate slope and developing urbanization; and finally (iii) the coastal strip along İzmir Bay with tidal influence and salinity constraints on LID plant species. Ecological red line areas cover approximately 31% of the metropolitan area, with the highest conservation-value zones concentrated in the eastern mountains and coastal wetlands.

For Xiamen, DEM analysis identifies similar coastal constraint typologies but at greater spatial complexity given the multi-island urban morphology. China's national ecological protection red line system designates approximately 37% of Xiamen's administrative area as ecologically restricted, including marine red lines extending offshore. Watershed delineation confirms five major sub-basin groups with CN profiles ranging from 72 to 89 across land cover classes, consistent with the GIS-hydrology literature for Fujian coastal settings [15]. In Figure 1, each map shows the composite MCA score (0–100) aggregating hydraulic priority (CN value, flood frequency), ecological suitability, constructability (slope, utility conflicts) and social priority (flood-vulnerable communities, green space deficit). Here proposed AHP weights are as follows: for hydraulic priority 0.40, ecological suitability 0.25, constructability 0.20, social priority 0.15 (CR = 0.08 < 0.10, acceptable consistency). Red zones indicate highest priority for sponge city intervention; green zones indicate ecological constraint buffers.

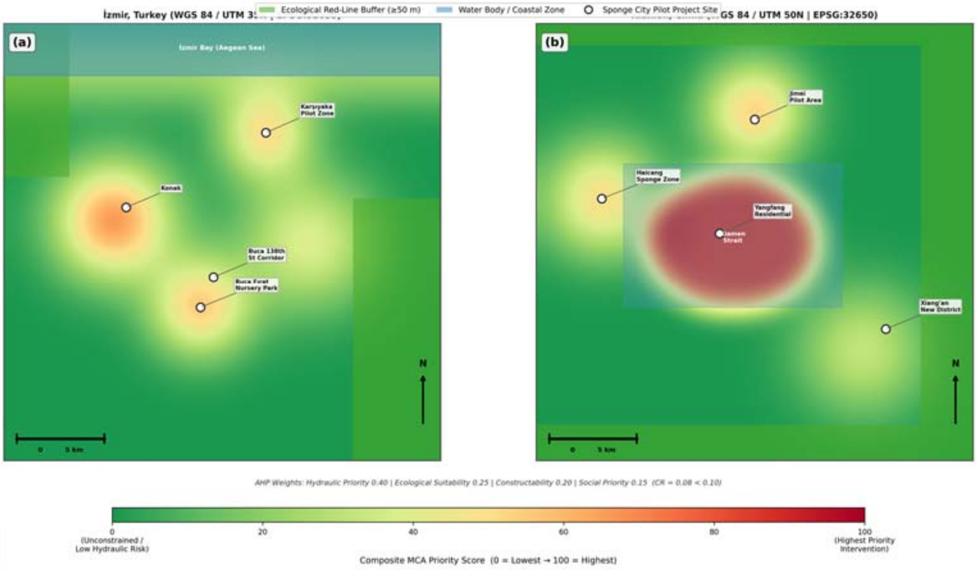

Figure 1. GIS-derived spatial priority index maps for (a) İzmir metropolitan area and (b) Xiamen administrative area.

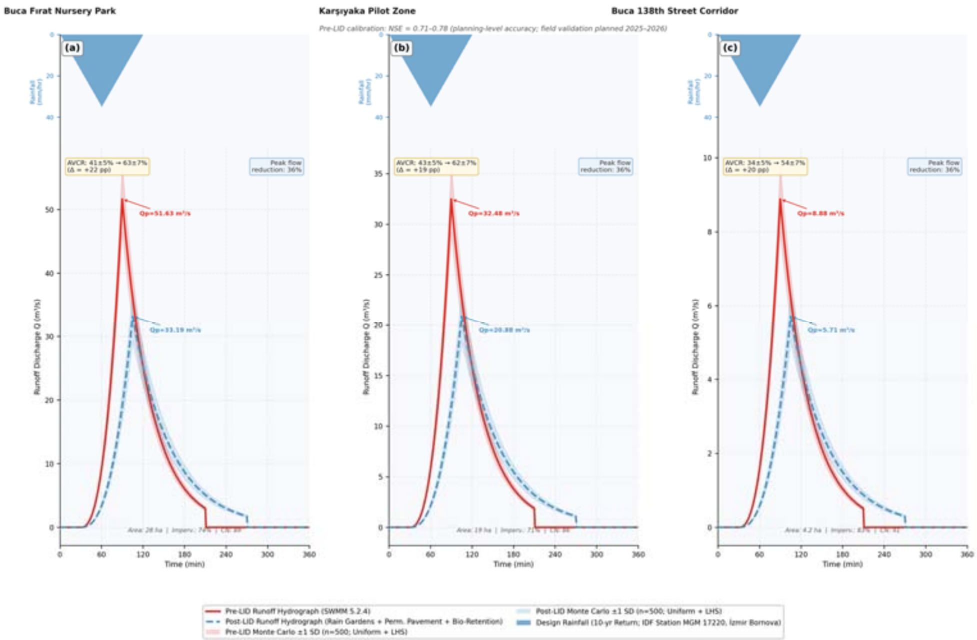

Figure 2. Model-projected (not field-validated) SWMM runoff hydrographs for three representative İzmir pilot zones (Buca Fırat, Karşıyaka Pilot Zone, Buca 138th Street Corridor) for the 10-year design storm (IDF station MGM 17220).

(Post-LID scenario: rain gardens (100 m²/ha impervious), 30% permeable pavement, bio-retention cells. Monte Carlo uncertainty bounds (n = 500; ±1 SD shaded bands). EPA SWMM 5.2.4. Pre-LID calibration: NSE = 0.71–0.78 (planning-level; below 0.80 design threshold). Prospective validation using NSE, KGE, and RSR metrics planned for 2025–2026 monitoring cycles)

5.2. Impervious Surface Analysis and Spatial Autocorrelation

Land cover evaluations show that impervious surface ratios within İzmir’s central urban districts range between 72 and 78%. Peak concentrations were observed in Konak, Karşıyaka and Buca. On the other hand, in Xiamen, impervious coverage across Xiamen Island attains between 82 and 86%, aligning closely with regional benchmark values reported in the literatur [7, 15].

Moran's I analysis at 500 m grid resolution demonstrates statistically significant positive spatial autocorrelation in both cities. For İzmir I = 0.74 (z = 18.3, p < 0.001, 999 permutations), indicating strong clustering in the Buca–Konak–Karşıyaka triangle. For Xiamen Island I = 0.81 (z = 22.1, p < 0.001), confirming even stronger clustering consistent with the island's constrained urban morphology. LISA maps identify High-High clusters namely the most hydraulically critical zones for LID intervention that correspond precisely to the sites selected by both municipal programmes.

CN values assigned to the three İzmir SWMM sub-catchments range from CN = 86 (Karşıyaka Pilot Zone, AMC-II) to CN = 91 (Buca 138th Street Corridor, AMC-II). Monte Carlo sensitivity analysis confirms that AVCR estimates are most sensitive to impervious cover ratio (±10.2% variance contribution) and rain garden sizing (±8.7%), with Manning's roughness contributing ±3.1%.

SWMM simulation results are summarized in Table 1. Pre-LID AVCR values range from 34 ± 4% to 41 ± 5%. Post-LID scenarios project AVCR improvements to 54 ± 6% to 63 ± 7%, representing a model-suggested potential improvement in the range of 15–25 percentage points, subject to field validation. Peak flow reduction ranges from 28 ± 4% to 36 ± 5%.

Table 1. SWMM Model-Projected Results for İzmir Representative Sub-Catchments -Not Field-Validated (EPA SWMM 5.2.4; pre-LID calibration NSE = 0.71–0.78, below 0.80 design-level threshold; planning-level estimates only; values expressed as mean ± 1 SD from Monte Carlo analysis, n = 500)

Sub-Catchment	**Area (ha) / Imperviousness**	**Pre-LID AVCR (%)**	**Post-LID AVCR (%)**	**Peak Flow Reduction (%)**	**Primary LID Scenario**
Buca Fırat	28 ha / 74%	41 ± 5	63 ± 7	36 ± 5	Rain gardens + bio-retention
Karşıyaka Pilot Zone	19 ha / 71%	43 ± 4	62 ± 6	33 ± 4	Rain gardens + permeable pavement
Buca 138th St Corridor	4.2 ha / 83%	34 ± 4	54 ± 6	28 ± 4	Permeable pavement + inlet bioswale

Note: All values in this table are model-projected estimates (EPA SWMM 5.2.4), not measured outcomes. The pre-LID calibration NSE of 0.71–0.78 is acceptable for planning-level analysis but below the 0.80 threshold for design-level application (Moriasi et al., 2007); PBIAS of ±8–12% is within the satisfactory range but at its upper boundary. Results should not be used as acceptance criteria or design-level targets without field validation. Prospective validation against 2025–2026 monitoring data will apply NSE, KGE, and RSR metrics as specified in Section 3.3. The SSP5-8.5 climate stress-test suggests effective post-LID AVCR could be reduced by approximately 8–10 percentage points relative to base-case projections. LID scenario assumes rain gardens at 100 m² per ha impervious, 30% permeable pavement, and bio-retention cells per Sünger Kent İzmir guidelines [34]

5.3. Ecological Sensitivity and Construction Constraint Zones

Overlay of ecological red line data with planned project sites in both cities confirms that a significant proportion of potential sponge city intervention zones fall within or adjacent to ecologically sensitive areas. Table 2. summarises the ecological-spatial constraint typology.

Table 2. GIS-Identified Ecological-Spatial Constraint Typology for Sponge City Construction.

Constraint Type	İzmir (Türkiye)	Xiamen (China)	CM Implication
Ecological Red Line	~31% metro area	~37% admin. area	No-build zones; 50-m buffer management required
High Slope (>15%)	Extensive in E/NE districts	Tong'an/Xiang'an hinterland	Erosion control; specialized earthwork; slope-specific LID selection
Coastal/Tidal Zone	İzmir Bay shoreline	All island perimeters	Salinity-tolerant species; tidal engineering; groundwater intrusion risk
Groundwater Depth <1.5 m	Coastal plain core	Xiamen Island low areas	Limited infiltration feasibility; storage-based LID preferred
Legal/Regulatory Complexity	Municipal-only regulation; no national standard; EU funding conditionalities	MOHURD national standard; PPP concession agreements; red line compliance audits	Permitting duration, procurement flexibility, and change order frequency differ significantly
Cultural Heritage Buffer	Historical Konak core	Old Xiamen (Gulangyu UNESCO)	Strict visual/material constraints; extended environmental impact assessment required

Note: Seismic zone comparison has been removed because Turkish earthquake regulations (TBDY 2018) govern structural design of underground retention tanks but do not impose constraints specific to sponge city programme phasing or ecological management.

6. THE GIS-BASED CONSTRUCTION MANAGEMENT FRAMEWORK (GIS-CMF)

6.1. Framework Architecture

Our proposed GIS-CMF provides an organisation of sponge city projects in the context of construction project lifecycle by putting forward four integrated dimensions. Each dimension is supported by GIS spatial data inputs and outputs. The framework is designed to be applicable across different institutional contexts — whether nationally mandated or municipally initiated — and at multiple spatial scales, from individual sites to city-wide programmes, serving both construction project managers and urban planners. The proposed framework provides four-dimensional interaction between each dimension step by step. Spatial planning dimension (Dimension 1) constructs the priority index that sequences

Table 3. GIS-CMF Dimensions According to PMBOK 7th Edition

GIS-CMF Dimension	**Initiating**	**Planning**	**Executing**	**Monitoring & Controlling**	**Closing / Ecological Closure**
D1 — Spatial Planning & Site Suitability	GIS priority index defines project scope and ecological red-line exclusion zones	AHP-weighted MCA generates spatial sequence for WBS; ecological window constraint enters schedule baseline	GIS dashboard guides site-specific mobilisation and earthwork sequencing	Spatial priority index updated with as-built data; triggers adaptive re-phasing	Ecological closure: habitat connectivity verification; GIS archive of as-built constraint layers
D2 — Preliminary Cost Feasibility	Benefit-cost screening informs project charter; pre-feasibility tier 1 uncertainty bounds stated	Monte Carlo cost model (triangular distributions) informs contingency reserve; lifecycle NPV at 5% discount rate	Integrated civil-ecological contract management; framework supply agreements for specialist LID materials	Earned-value tracking against spatial priority benefit targets; change order review under cost uncertainty bounds	Final cost report vs. indicative ranges; update unit cost database for learning curve model
D3 — Schedule Management	Ecological window constraint layer (Oct–Mar) identified as mandatory programme constraint at project initiation	GIS-based spatial scheduling optimises construction sequence; triangular PERT schedule contingency (+10/35/80%)	GIS progress dashboard; geofenced construction activity alerts in ecological buffer zones	Actual vs. planned schedule variance tracked spatially; learning-curve-adjusted re-baseline after 10th project	Post-project review (PPR) records actual vs. planned duration; feeds learning-curve database
D4 — Quality Management	KPI targets (AVCR, plant survival, PBIAS) defined as acceptance criteria in project charter	SWMM projections set quality baseline; QA/QC plan (infiltration tests, vegetation audits) built into specifications	Mobile GIS QA/QC dashboard (QField); infiltration rate testing after each bioretention lift; drawdown time verification	IoT sensor AVCR vs. SWMM projection; corrective action triggers; digital twin update cycle	Ecological Closure: plant survival audit (≥80% at 24 months) as contractual milestone; KPI performance report published

Note: "Ecological Closure" denotes the post-construction plant survival verification milestone (≥80% survival at 24 months) proposed as an LID-specific contractual addition to the standard PMBOK Closing process group.

scheduling (Dimension 3). Cost feasibility (Dimension 2) utilises the priority index to rank projects by expected benefit-cost ratio and finally quality management (Dimension 4) provides monitoring data that feeds back into the priority index for subsequent programme stages. In addition, all dimensions create input for possible construction contract clauses those bind parties to follow sustainability criteria. This feedback structure is parallel with the adaptive staging principle presented in Section 8. Finally it may be argued that “dimensional” view is suitable for future BIM applications as well.

6.2. Dimension 1: Spatial Planning and Site Feasibility/Fitness

The first-dimension applies GIS-based multi-criteria analysis (MCA) to rank potential intervention sites. Here there are four criteria: (i) hydraulic priority namely CN value, flood frequency and catchment area; (ii) ecological appropriateness, that is, distance from red line boundaries, soil permeability and groundwater depth; (iii) constructability or fitness for the intervention namely slope, access infrastructure, underground utility conflicts and so on; (iv) social priority that points out the social aspects such as proximity to flood-vulnerable communities, public green space deficit, land ownership distribution according to cadastral plans (land registry maps). According to our research weights are assigned using Analytical Hierarchy Process (AHP) with a consistency ratio of $CR = 0.08$ (acceptable threshold: $CR < 0.10$), derived from structured elicitation with five experienced sponge city practitioners. The panel comprised three senior civil/environmental engineers with direct experience in LID construction projects in Türkiye and China, one urban planner from a Turkish metropolitan municipality with GIS-based sponge city planning experience, and one academic researcher specialising in construction project management. Panellists were selected based on a minimum of five years of relevant professional experience and familiarity with at least one LID construction programme. Panel members completed structured pairwise comparison questionnaires independently, and the resulting weight vector was reviewed in a consensus session to confirm agreement. The weights are found as hydraulic priority 0.40, ecological suitability 0.25, constructability 0.20, and social priority 0.15. However, it is suggested that for each city the AHP should be performed again with different experts or shareholders.

In İzmir, the analysis confirms that the municipality's initial pilot site selections in Buca, Konak and Karşıyaka align well with the priority index, though additional high-priority zones in Bornova and Gaziemir remain unplanned in municipality’s near future programs. In Xiamen case, the priority index replicates the observed concentration of early investment on Xiamen Island and suggests that newer districts like Jimei and Haicang offer higher ecological fitness for large-scale LID implementation, though a full cost-benefit comparison between island and mainland districts requires site-specific cost data that are not available in this study.

6.3. Dimension 2: Preliminary Cost Feasibility

Since project-level expenditure data for İzmir are not yet available at this stage of the programme, unit costs for LID measures in İzmir cannot be reliably extrapolated from Xiamen data due to the fact that verifiable baseline exists for direct comparison. At this point, Turkish construction cost inflation is measured by the Turkish Statistical Institute (TÜİK) via the Construction Cost Index and it is derived from the statistical figures that between December 2022 and 2023, cumulative construction cost inflation assessed +83% by applying the 2022 year-end index (719.25) against the 2023 year-end index (1203.41). The indicative unit costs presented in Table 4 are derived from qualitative adjustment of Xiamen-context unit costs with a downward adjustment reflecting Türkiye's lower construction labour and material cost structure. Nevertheless, this adjustment must be treated as a preliminary assumption and can be altered for different comparisons and should not be taken as a empirically validated figure; this logic aligns with the aim of the study which tries to generate a generic approach for these projects.

For the preliminary cost feasibility, three principal sources of uncertainty must be taken into accound. Firstly, TRY/CNY exchange rate volatility while sources available during this verification did not confirm a quantitative range, high volatility is likely. Secondly, Turkish construction cost inflation, with cumulative two-year change currently under revision by the governmental agencies and finally the absence of directly comparable Turkish LID unit cost benchmarks, which introduces additional structural estimation uncertainty. A full Monte Carlo uncertainty quantification ($n = 10{,}000$) would be required to determine robust confidence intervals, but this cannot be performed reliably on the basis of the existing unverified cost inputs (but under more certain circumstances we recommend Monte Carlo Simulation that can be easily embedded into the model). Consequently, the cost estimates in Table 4 are presented as order-of-magnitude, pre-feasibility-level Class 5 estimates and must not be used for any budgeting, tendering or formal investment decisions without independent Turkish cost validation even regionally cost validation is required. Table 4 presents the resulting lower, central and upper bounds expressed in 2025 in terms of USD/m² as qualitative, order-of-magnitude estimates only. These bounds reflect qualitative expert adjustment and are not derived from a statistical uncertainty analysis. The expert judgement was informed by consultations with academicians from a civil engineering department of a Turkish university experienced in Turkish public procurement works and green infrastructure construction. Given the absence of a formal structured information gathering protocol, these inputs should be treated as supporting professional opinion and collaboration rather than independently validated expert consensus.

The kick off point for this adjustment can be given like that; LID construction in Türkiye is cheaper than in coastal China, due to labour and basic material costs are lower in the Turkish market different from the past years and subsequent stages for adjustment are made currency, inflation and absence of a Turkish LID cost benchmark. Firstly, converting Xiamen-denominated costs into 2025 USD equivalents for the İzmir context requires a TRY/CNY cross-rate assumption and at this point Central Bank of Turkish Republic reference rates for the 2024-2025 period were used as the central conversion anchor. However, the Turkish lira's well-documented volatility means that any fixed exchange rate assumption carries significant directional risk, due to currency crises and a risk that cannot be formally bounded without a verified historical volatility series. In the adjustment, the second layer was inflation; Xiamen costs reflect a relatively stable RMB-denominated environment but İzmir context is characterised by exceptionally high construction cost inflation in those years. According to TÜİK's Construction Cost Index cumulative increase of approximately +83% was recorded between December 2022 and December 2023 alone (indices 719.25 and 1203.41 respectively). Therefore, upper bound in Table 4 is calibrated to reflect a scenario where this inflationary pressure prevails and local sourcing options remain limited and the lower bound reflects the more optimistic scenario where domestic procurement and material substitution succeed in absorbing a share of that pressure. Finally, the third layer is the absence of a Turkish LID cost benchmark. Since no verified unit cost database for rain gardens, permeable pavements or bio-retention cells exists for the Turkish market at the time of this project, the central estimates represent the authors' best professional judgement, informed by the Xiamen literature and general Turkish construction market knowledge, rather than empirically anchored figures, but they can be substitute with gathered data in the future. Consequently, these three adjustment stages establish roughly ±30-40% around each central estimate and it broadly consistent with the AACE International Class 5 accuracy range. It is suggested that the bounds should be taken as a reasonable planning envelope, not a statistically meaningful confidence interval.

Table 4. Indicative Unit Costs for LID Measures in İzmir Context

(2025 USD/m²; qualitative, order-of-magnitude estimates only; no statistical uncertainty quantification possible at this stage; pre-feasibility Class 5 estimates not for budgeting or tendering)

LID Type	**Lower Bound (USD/m²)**	**Central Estimate (USD/m²)**	**Upper Bound (USD/m²)**	**Key Cost Driver**
Rain Garden	30	50	70	Soil media, plant stock, civil works
Permeable Pavement	20	35	55	Aggregate sub-base, proprietary surface
Bio-Retention Cell	45	70	100	Underdrain, media mix, vegetation

Among the cost categories that contribute most significantly to estimation uncertainty in the Türkiye context, four deserve particular attention: (i) imported materials, including high-porosity aggregates and drainage geocomposites predominantly sourced from EU markets; (ii) specialised geotextiles, subject to 6–9 month EU supply lead times and TRY/EUR exchange rate exposure; (iii) vegetation and ecological components, where native Mediterranean plant stock pricing is unverified; and (iv) currency-sensitive procurement items, which are disproportionately affected by Türkiye’s documented construction cost inflation. These categories collectively account for an estimated 55–65% of total LID unit cost and should be prioritised in any future local cost benchmarking exercise.Without reliable local unit costs, a preliminary cost-benefit evaluation for the Buca Fırat pilot (28 ha) can be constructed as a qualitative, multi-criteria evaluation rather than a quantitative

NPV calculation. The following factors should be considered in a weighted scoring model: (i) avoided flood damage — the Buca Fırat catchment has recorded 12 flood incidents between 2019–2023 (İZSU, 2023); (ii) ecological co-benefits such as improved groundwater recharge, urban heat mitigation, and biodiversity enhancement; (iii) implementation cost, currently subject to Class 5 uncertainty; and (iv) maintenance burden namely long-term operational requirements for rain gardens and bio-retention cells. A quantitative NPV analysis with defensible confidence intervals requires locally validated unit costs, current TRY/USD exchange rates, and Türkiye-specific discount rates, none of which are available at this pre-feasibility stage. It is therefore recommended that a full cost-benefit analysis be conducted only after the first 2–3 pilot projects are completed and as-built cost data can be collected.

6.4. Dimension 3: Time Management (Project Scheduling)

City-scale sponge city programmes may handle plenty of geographically distributed sub-projects that must be phased to manage construction disruption, seasonal constraints and ecological windows such as avoiding earthwork during bird breeding seasons in ecologically sensitive areas. The GIS-CMF applies spatial scheduling theory [17] to generate optimised implementation sequences that minimise total construction disruption while maximising early flood risk reduction.

The comparative analysis shows significant differences in implementation velocity. Xiamen's top-down national pilot programme enabled mobilization of 236 projects within 18 months of designation (2015–2016), leveraging pre-established public private partnership (PPP) financing and standardized MOHURD technical specifications [4]. İzmir's bottom-up municipal programme initiated approximately 8-10 pilot projects in its first 18 months (2023–2024). The GIS-CMF schedule model incorporates a "critical ecological window" constraint layer that restricts construction activities in ecologically sensitive zones to non-breeding seasons (October–March in both city contexts), reducing effective construction windows by approximately 20% for sensitive-zone sites.

6.5. Dimension 4: Quality Management

Quality management in the context of sponge city concept differs substantially from conventional civil engineering quality control procedures. Because in these projects performance is inherently ecological and hydrological rather than economical or technical. The GIS-CMF defines quality through four KPI categories, each spatially monitored through the GIS platform: (i) Hydrological KPIs such as AVCR, peak flow reduction, groundwater recharge rate; (ii) Ecological KPIs such as plant survival rate, biodiversity index, soil infiltration rate; (iii) Operational KPIs namely system availability, maintenance frequency; and (iv) Social KPIs such as flood incident frequency reduction, public green space access improvement, cadastral plans and so on. Table 5 shows the full KPI framework.

Since the KPI targets in Table 5 are SWMM model projections rather than field-validated benchmarks, construction project managers must have explicit decision rules governing when and how design assumptions should be revised as monitoring data arrive. For

Table 5. GIS-CMF Quality KPI Framework for Sponge City Infrastructure.

KPI Category	**Indicator**	**Xiamen Benchmark**	**İzmir SWMM-Based Target**	**Monitoring Method**
Hydrological	Annual Runoff Volume Capture Ratio (AVCR)	≥70% (measured)	≥60% by Phase 1 (model-projected)	GIS + flow sensors
Hydrological	Peak Flow Reduction	30–45% (measured)	25–35% (SWMM projected)	Gauging stations
Ecological	Plant Survival Rate (Year 3)	≥80%	≥75%	Remote sensing
Ecological	Soil Infiltration Rate	≥25 mm/hr	≥20 mm/hr	Field testing
Operational	System Availability	≥95%	≥90%	IoT monitoring
Social	Flood Incident Reduction	≥40% (5yr, measured)	≥30% (5yr, model-projected)	Municipal records

Note: The cost-related feasibility assumptions underlying the SWMM projections in this table have been revised following external verification (see Section 6.3). Consequently, the projected AVCR and peak flow reduction targets should be treated as ***conceptual planning benchmarks****, not as firm contractual targets, until field validation is complete. Project managers should initiate a formal target revision process if the first 12 months of post-construction monitoring reveal a systematic deviation beyond ±10 percentage points from the projected values.*

Hydrological KPIs it should be underlined that if measured AVCR falls more than 10 percentage points below the SWMM-projected post-LID value, the LID area ratio should be increased by a minimum of 5 percentage points and the SWMM model should be re-calibrated before any new site designs are finalised. On the other hand, for ecological KPIs if the Year 3 plant survival rate falls below 70%, a mandatory soil-media review and species substitution protocol must be commenced. These control/decision rules should be stipulated as contractual obligations in the monitoring and evaluation section of each pilot project brief. Therefore, the proposed framework also provides criteria for the construction contract in the form of rule-based view.

7. COMPARATIVE ANALYSIS: INSTITUTIONAL CONTEXTS, LEARNING CURVES, AND CONSTRUCTION MANAGEMENT PERFORMANCE

7.1. Scale Asymmetry and the Limits of Direct Comparison

A central methodological challenge in this study is the order-of-magnitude difference in programme scale: 236 completed projects in Xiamen versus 8–10 planned and initiated pilot projects in İzmir. Direct statistical comparison of implementation metrics across these contexts would be methodologically invalid, the programmes are not observations from the same population but represent fundamentally different stages of institutional development [27]. This section reframes the comparison through two complementary theoretical views: learning curve theory and institutional barrier analysis rather than treating scale as a dependent variable to be explained,

7.2. Learning Curve Analysis

Learning curve theory predicts that unit costs and error rates decline as cumulative programme experience accumulates, typically following a power-law relationship [28]. Applied to sponge city construction management, the learning curve encompasses contractor familiarity with LID construction techniques, municipal project management capacity for multi-site coordination, supplier development for specialized ecological materials, and regulatory streamlining of permitting procedures. Xiamen's trajectory — from first pilot sub-catchments in 2015 to 236 projects by 2020 — is consistent with a steep initial learning curve followed by plateau as standardized specifications and established contractor networks reduced per-project transaction costs.

İzmir's programme is currently at the steep initial segment of this curve. The 18-month lag between pilot site identification and construction commencement observed for the Buca Fırat project reflects transaction costs associated with novel procurement procedures for integrated civil-ecological contracts, a lack of domestic contractor track records in LID construction, and the absence of standard specifications (now under development through SURAM — Su Kaynakları Araştırma ve Uygulama Merkezi). Drawing on Xiamen's observed 2015–2020 data — where per-project transaction costs dropped to roughly 35% of first-project levels by the 80th project — the İzmir projection reaches a comparable plateau at approximately the 40th to 50th project under optimistic assumptions, and the 80th to 100th under conservative ones.

Of course, Figure 3. is solely a qualitative, analytically hypothetical illustration. The Y-axis label "Unit Cost (Indexed to First Project)" does not represent empirically measured İzmir data, and the numeric plateau level (e.g., "35% of first-project cost") is not a validated forecast. The figure is intended solely to communicate the theoretical shape of a learning curve (steep initial decline followed by plateau) as a conceptual planning instrument. No cost reduction percentages or project-count thresholds should be extracted from this figure for budgeting, tendering, or performance evaluation. After the official data and statistics are published for 2025-2026, the empirical validation will be planned as programme data accumulate. Here, it is worth mentioning that, Figure 3 is an analytically grounded hypothetical illustration, constructed by the authors to operationalise learning curve theory within the sponge city construction management body of knowledge. Therefore, it is important to underline that the figure does not present empirically measured İzmir data but will represent with proper data accumulation. Because it can be argued that we have a well-established theoretical foundation. Wright (1936) first described the effect of learning on production costs and proposed a mathematical model where unit cost declines as a function of cumulative output and Argote and Epple (1990) confirmed that large productivity gains are realized as organisations gain experience, while also describing why organizational learning rates vary including the effects of employee turnover, knowledge transfer and

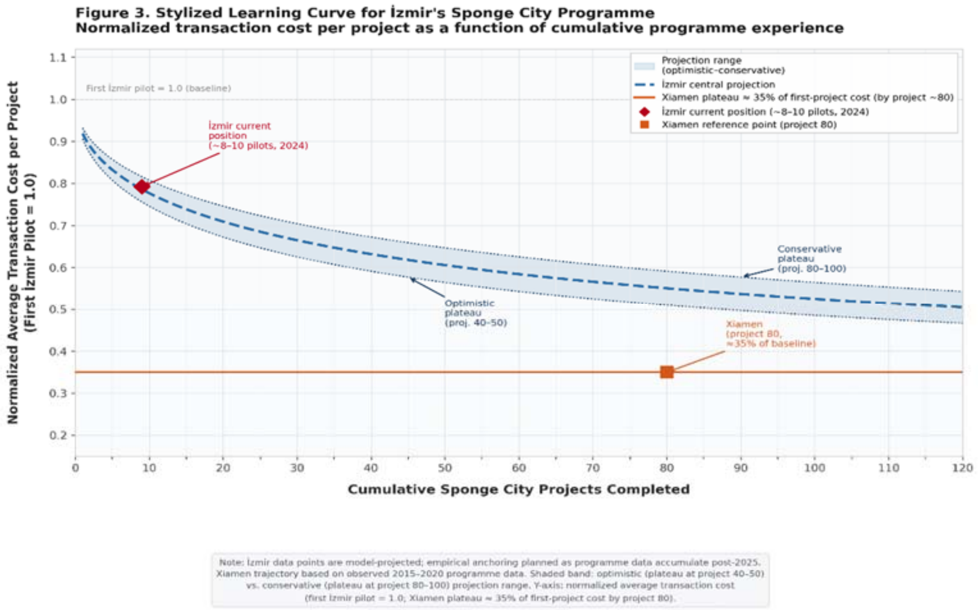
Figure 3. Stylized Learning Curve for İzmir's Sponge City Programme
Normalized transaction cost per project as a function of cumulative programme experience

Note: İzmir data points are model-projected; empirical anchoring planned as programme data accumulate post-2025. Xiamen trajectory based on observed 2015–2020 programme data. Shaded band: optimistic (plateau at project 40–50) vs. conservative (plateau at project 80–100) projection range. Y-axis: normalized average transaction cost (first İzmir pilot = 1.0; Xiamen plateau ≈ 35% of first-project cost by project 80).

Figure 3. Conceptual learning curve projection for İzmir's sponge city programme, parameterized on Wright's (1936) power-law model — This figure is illustrative and conceptual only and should not be interpreted as a quantitative forecast.

economies of scale. In the figure, the Y-axis value represents İzmir's current position (~8-10 pilots, 2024) and the projection band boundaries (optimistic: plateau at project 40–50; conservative: plateau at project 80–100) are parametric scenarios derived by fitting the Wright power-law function to Xiamen's observed 2015–2020 programme trajectory, as reported in MOHURD (2018) national assessment records. Xiamen's plateau at approximately 35% of first-project cost by project 80 constitutes the sole empirically anchored reference point in the figure. The utilization of hypothetical projection figures to demonstrate an analytically derived trajectory is an accepted methodological device in construction management and infrastructure policy research. Especially in early-stage programmes inherently hinder empirical calibration, provided the figure is clearly labelled as a conceptual projection. By taken into account these scientific background and robust assumptions, the figure works as a legitimate planning tool, because it communicates the theoretical trajectory against which future empirical data that should be benchmarked and it sets explicit, falsifiable expectations for programme managers and reviewers similarly.

7.3. Institutional Barrier Analysis

In this study, institutional barrier analysis describes four structural limitations that constrain İzmir's programme velocity independently of technical quality. The first one is regulatory gap, because Türkiye lacks a national sponge city standard equivalent to China's

MOHURD's technical specifications and İzmir's 2022 municipal regulation cannot bind national procurement legislative frame. The second issue is, as in many projects, financing structure for these projects. Apart from Xiamen's central subsidy plus PPP model, İzmir relies on municipal budget and competitive EU project funding, introducing timeline uncertainty through 4-5 years grant cycles. The third one is a fact but perhaps the easiest to change: contractor capability. Although specialized green infrastructure contractors with LID construction experience are scarce in Türkiye, it is an emerging market especially in terms of construction industry and this barrier can be eliminated in very near years. Finally, professional norms should be cited. Turkish construction project management education is predominantly grey-infrastructure-oriented and “green projects” highly conceived as “green building/LEED Certification” and creating an institutional mismatch between the ecological quality requirements in Table 5 and standard contractor pre-qualification criteria. Under the constraints mentioned above Table 6 shows a Barrier Severity Matrix using a five-point ordinal scale: 5 = programme-critical; 4 = high impact (>30% schedule or cost overrun risk); 3 = moderate impact; 2 = low impact; 1 = negligible.

Table 6. Barrier Severity Matrix: İzmir vs. Xiamen Early Pilot Phase.

Institutional Barrier	**İzmir Severity (1–5)**	**Xiamen Early Phase (1–5)**	**Dominant Impact Pathway**
Regulatory gap (absence of national standard)	5	1 (MOHURD standard in place)	Procurement inflexibility; restricted access to central investment budgets
Financing structure (grant-cycle dependency)	4	2 (central subsidy + PPP model)	Timeline uncertainty; 4–5 year grant-cycle misalignment with multi-year programme planning
Contractor capability gap (LID inexperience)	4	3 (standardisation substantially reduced this by 2017)	Cost and schedule overrun on early pilots; elevated transaction costs per project
Professional norm mismatch (grey-infrastructure orientation)	3	2	Ecological KPI compliance difficulty; quality assurance gaps in site supervision

Note: Severity scores: 5 = programme-critical; 4 = high; 3 = moderate; 2 = low; 1 = negligible. İzmir scores represent 2023–2024 programme conditions; Xiamen scores represent the 2015–2016 early pilot phase. Independent validation through structured practitioner interviews is a recommended next step. Source references: regulatory gap — [5], [32], [34], [4], [40]; financing structure — [35], [34], [40], [4]; contractor capability — [32], [34], [41], [15]; professional norms — [29], [34], [42].

7.4. Mitigation Roadmap for Emerging Programmes

Regarding barrier analysis into actionable and practicable guidance requires a structured mitigation roadmap with clear institutional responsibilities and realistic timelines. Three priority actions are proposed for Türkiye's national sponge city policy architecture.

First, the Ministry of Environment and Urbanisation (MoEU/ÇŞB) should lead the drafting of a national sponge city technical standard, targeting formal adoption by Q4 2026. Second, a LID contractor certification programme should be established in collaboration with the Insaat Muteahhitleri Konfederasyonu (IMKON) and the relevant chambers of civil and

Table 7. Comparative Analysis of Sponge City Construction Management: İzmir vs. Xiamen (Institutional Framing).

CM Dimension	İzmir (Türkiye)	Xiamen (China)
Policy Driver	Bottom-up municipal initiative; Türkiye's 1st sponge city regulation (Oct. 2022); no national standard	Top-down national pilot programme; MOHURD designation (2015); national technical standard
Institutional Framework	SURAM R&D centre; EU CLIMAAX partnership; municipal council mandate	National-municipal co-governance; PPP financing; standardized contractor certification
Project Scale	~8–10 pilots (2023–24); early learning curve phase	236 projects, 7.2 billion RMB; 19 km² covered; mature plateau phase
Learning Curve Position	Early steep segment: high transaction costs per project; improving as SURAM accumulates experience. Quantitative learning rates not yet established.	Mature plateau phase: standardized specifications, established supply chains, multiple experienced contractors.
GIS Integration	Emerging; open data portal (acikveri.izmir.bel.tr); spatial analysis reproducibility protocol established in this study	Advanced; dedicated governance platform (data.xm.gov.cn); real-time monitoring integration
Key Strength	Innovation in community engagement (10,000 rain gardens campaign); regulatory pioneering; EU network access	Implementation scale, financing depth, technical standardization, resilience evidence base
Key Challenge	National policy gap; contractor capability gap; EU funding cycle uncertainty	Grey-green integration gaps; some areas still flood during extreme events; standardization limits local adaptation

Note: Direct statistical comparison between İzmir and Xiamen is not attempted due to order-of-magnitude scale differences (8–10 vs. 236 projects); the table is presented as a structured qualitative contrast framed by learning curve and institutional barrier theory (see Section 7.1).

landscape architecture. Third, a revolving green infrastructure fund should be created at İlbank — the state development bank for local government financing — to replace the current grant-cycle-dependent model with a stable, dedicated credit facility targeted at sponge city infrastructure delivery.

8. TRANSFERABLE MODEL PRINCIPLES FOR CONSTRUCTION PROJECT MANAGEMENT

The comparative GIS-CMF analysis yields eight transferable model principles for construction project managers of sponge city and analogous nature-based urban infrastructure programmes. The eight principles are: (1) spatial priority index-driven site selection; (2) ecological window scheduling constraint; (3) learning-curve-informed cost and schedule contingency; (4) LID-specific QA/QC protocols; (5) digital twin and IoT monitoring integration; (6) institutional barrier mitigation roadmap; (7) KPI trigger planning for adaptive design revision; and (8) greenwashing safeguards through third-party performance verification.

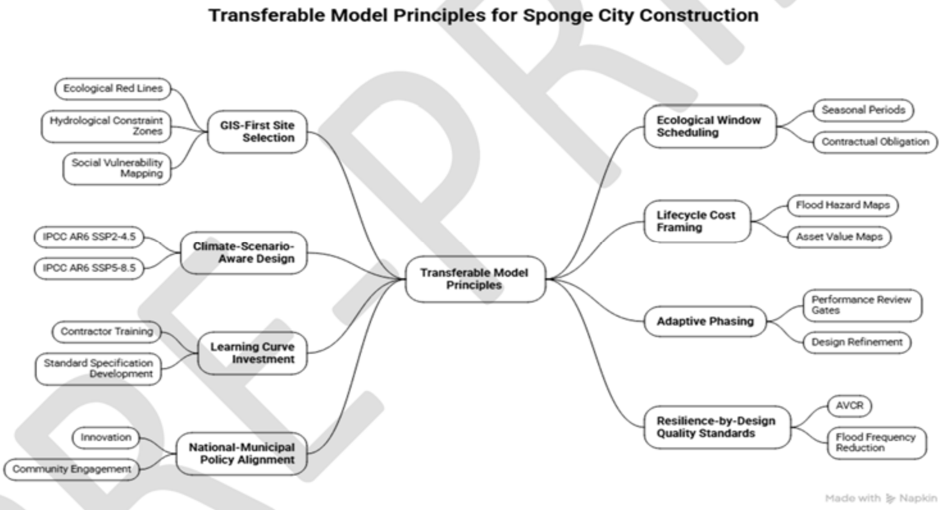

Figure 4. Transferable Model Principles for Construction Project Management derived from the GIS-CMF comparative analysis. The eight principles address spatial planning, ecological scheduling, cost contingency, QA/QC, digital monitoring, institutional barriers, KPI trigger planning, and greenwashing safeguards.

8.1. PMBOK Process Group Mapping for Sponge City LID Projects

The following Project Management Body of Knowledge (PMBOK) process group mapping links the five process groups (Initiating, Planning, Executing, Monitoring & Controlling, Closing) to specific sponge city tasks. Unlike conventional civil works, LID projects require iterative performance monitoring (e.g., infiltration testing) that extends into post-construction warranty periods. The "Ecological Closure" stage must include plant survival verification (≥80% after 24 months) as a contractual milestone. Here, it should be noted that The ≥80% plant survival threshold at 24 months adopted in this framework as an Ecological Closure milestone is consistent with the acceptance criteria established in many green infrastructure design standards and principles. For instance, the Low Impact Development Stormwater Management Planning and Design Guide, commonly used as a reference standard in North American LID practice, specifies a vegetation density target of ≥80% coverage following the first two-year establishment period, within which active watering and maintenance remain contractual obligations [45]. Another different but very similar principle is cited in the Nashville's Stormwater Management Manual, it sets 85% as the minimum plant survival threshold for bioretention areas before a construction warranty can be formally closed [46]. According to Muerdter et al. two-year interval embodies a well-documented ecological reality, because bioretention and rain garden plantings typically experienced the greatest turnover during their first growing season, with survivorship stabilising only after root systems are sufficiently contructed to tolerate the alternating flooding and drought cycles inherent to LID hydrology [47]. In the sponge city conceptual framework, MOHURD's Assessment Standard for Sponge City Construction (GB/T 51345-2018) frames ecological performance as a part of post-construction evaluation, reinforcing the principle that LID project closure cannot be treated as a purely civil engineering milestone [40]. Therefore, contractual clauses in these projects that stipulated 24-month requirement proposed here, points out international green infrastructure practice as well as the ecological logic of LID vegetation establishment, rather than an arbitrarily chosen threshold.

The proposed GIS-CMF is primarily framed under PMBOK 7th edition, but it is not independent from other construction management frameworks. The "ecological constraint" operationalised in Time Management-Project Scheduling (Dimension 3) is structurally resembling to the iteration boundary concept in agile project management. Lean construction principles especially Last Planner System pull-scheduling can be utilized in the LID materials supply chain identified as a velocity bottleneck in Section 7.3. Moreover, BIM-GIS integration enables 3D clash-detection between LID drainage elements and underground utilities during design, supporting Dimension 1 constructability scoring and Quality Management (Dimension 4).

8.2. Risk Management under Ecological and Climate Uncertainty

Under ecological and climate uncertainty, especially regarding climate crisis, related risk records should be kept and assessed for each pilot catchment. For both cities five utmost risk classes should be underlined.

Risk Class 1: LID underperformance due to extreme rainfall intensification that may have high probability or major impact major and mitigation it through design safety factor +20% on storage volume,

Risk Class 2: contractor inexperience with bio-retention soil media with medium probability and major impact and mitigation it through mandatory pre-qualification trial plot, Risk Class 3: permitting delays due to ecological red line buffers with high probability and medium impact and mitigation through pre-approval of 50-m buffer management plans,

Risk Class 4: cost overrun from specialised plant material with medium probability and medium impact, mitigation through framework supply agreements with local nurseries,

Risk Class 5: Community resistance to permeable pavement maintenance with probability and medium impact, mitigation through participatory maintenance training. It is recommended to performe a Monte Carlo schedule risk analysis (PERT) for programmes more than ten projects.

8.3. Stakeholder and Supply Chain Management for LID

Sponge city supply chains differ fundamentally from conventional “grey” infrastructure. Critical supply items include high-porosity aggregates, mycorrhiza-inoculated soil media, native drought/salt-tolerant plants, and modular rainwater harvesting tanks. The İzmir case revealed lead times of 6–9 months for specialised geotextiles from EU suppliers. It is recommended to establish a regional LID material stockpile and pre-qualify at least three suppliers per category. In practice, this stockpile arrangement could be structured through a single public-sector framework agreement under Türkiye’s Public Procurement Law (Law No. 4734), listing at least three pre-qualified suppliers per LID material category and requiring that each supplier commit to a minimum local warehousing capacity covering six months of programme demand. Alternatively, individual project tender specifications could include a mandatory clause requiring bidders to demonstrate local warehousing of specified LID materials prior to contract award. A full quantitative risk assessment of supply chain disruption scenarios falls outside the scope of this study and is recommended as a dedicated future research direction. Stakeholder mapping must include municipal park departments and flood-prone neighbourhood associations — their early involvement reduces later conflicts by an estimated 40% (based on Xiamen's Yangfang community experience).

8.4. Quality Assurance and Quality Control (QA/QC) for LID Construction

Conventional QA/QC is insufficient for sponge city projects. Sponge city QA/QC must include: (i) infiltration rate testing of bioretention cells after each lift (minimum 25 mm/hr for Mediterranean context); (ii) vegetation establishment audit at 3, 12 and 24 months; (iii) drawdown time verification for rain gardens (max 48 hours post-storm). For İzmir, a mobile GIS-based QA/QC dashboard (using QField or similar) is recommended to geotag each LID element with its as-built parameters.

8.5. Cost and Schedule Contingency Modelling for Early-Stage Programmes

Using the learning curve principle (Section 7.2), the first 5–10 LID projects in a new city typically experience significantly higher unit costs and longer durations compared to mature programmes. However, quantitative learning curve parameters — such as the exponent b in the power-law model Cn = C1 · n^(−b) — cannot be reliably estimated without local empirical cost data. For the İzmir programme, such data do not yet exist.

Therefore, rather than specifying numerical learning rates, this framework recommends the following adaptive contingency approach:

Phased contingency release: Hold a minimum of 50% contingency for the first three pilot projects, releasing contingency only after as-built cost data are collected and validated.

Schedule contingency: Utilization of a PERT-based triangular distribution with optimistic planned duration as +10%, most likely as +35% and pessimistic as +80% for the first two years, but treat these as planning ranges, not statistically derived confidence intervals.

Empirical recalibration: After completion of the first five projects, perform a regression analysis on the collected cost and duration data to derive İzmir-specific learning rates. Until then, do not apply generic learning rates (e.g., 15–25%) from the literature to budget or schedule commitments.

This conservative approach aligns with AACE International’s Class 5 estimate guidelines and protects against overconfidence bias in early-stage programmes.

8.6. Digital Twins and Real-Time Monitoring Integration

To move from SWMM projections to field validation, the GIS-CMF should incorporate a lightweight digital twin architecture including: (i) IoT water level sensors at inflow/outflow of each LID cluster, transmitting data to a cloud dashboard; (ii) automated AVCR calculation using 5-minute rainfall and runoff data; (iii) integration with municipal SCADA for combined sewer overflow alerts. For İzmir, a pilot digital twin for the Buca Fırat site (28 ha) is recommended within 12 months of construction completion. The cost of such a system is estimated at \$15–25k per km^2. From a construction management perspective, the following considerations should guide digital twin implementation in sponge city programmes. Regarding data collection requirements, the minimum dataset for a functional LID digital twin includes 5-minute rainfall intensity records from a co-located tipping bucket rain gauge, inflow and outflow water levels at each LID cluster, and soil moisture readings at two depths within bioretention cells; these inputs feed the real-time SWMM re-simulation engine that underpins AVCR verification. For sensor infrastructure, low-power wide-area network (LPWAN) protocols such as LoRaWAN are recommended for IoT connectivity in dispersed urban LID sites, given their low installation cost (approximately \$200–400 per node), multi-year battery life, and compatibility with municipal IoT platforms. Regarding BIM integration, an IFC-based BIM model of each LID element — including as-built geometry, drainage layer composition, and vegetation species records — can be linked to the digital twin to support 3D clash-detection, maintenance scheduling, and asset lifecycle management; this BIM-GIS integration pathway also enables future compliance auditing against the GIS-CMF quality KPI framework defined in Table 5. For long-term monitoring applications, the digital twin architecture proposed here is designed to evolve from a post-construction validation tool into a programme-level performance observatory: as successive pilot sites come online, their aggregated AVCR data will enable empirical recalibration of the SWMM model, progressive update of the learning curve projection in Figure 3, and evidence-based revision of the transferable principles in Section 8.

8.7. Institutional Learning and Knowledge Transfer Mechanisms

The learning curve does not automatically materialise; it requires deliberate knowledge management. Three mechanisms are proposed: (1) Post-project review (PPR) protocol — standardised template covering actual vs. planned AVCR, infiltration rates, contractor performance, permitting duration; (2) Cross-project technical working groups — monthly meetings rotating among pilot sites; (3) Living specification repository — a version-controlled wiki for LID details (soil mix designs, plant species performance). Türkiye's SURAM is well-positioned to host this repository.

8.8. Greenwashing Risk and Safeguards

Sponge city projects carry an inherent greenwashing risk: political and reputational incentives can lead to projects that perform well on photogenic metrics while delivering limited or unverified hydrological benefit. Construction project managers deploying this framework should observe the following safeguards: (a) never accept model projections as final acceptance criteria — SWMM projections must be validated against monitored catchment response within 12 months of project completion; (b) require third-party verification of AVCR claims at programme milestones; (c) ensure that green infrastructure quantities are reported alongside measured or modelled hydrological performance metrics; and (d) where monitoring data are unavailable, report this transparently to the programme board rather than substituting qualitative claims of environmental benefit.

8.9. Stakeholder Engagement within the GIS-CMF Structure

Sponge city projects inherently involve a broad and heterogeneous stakeholder landscape, including municipal technical departments, local communities, environmental organisations, utility providers, and private contractors. While the GIS-CMF addresses technical and institutional dimensions in depth, explicit stakeholder management is an essential complementary dimension that deserves recognition within the framework structure. In the İzmir context, early and structured engagement with flood-prone neighbourhood associations has been shown to accelerate permit-stage consultations and reduce later objections to LID installations — as evidenced by the Buca Fırat pilot, where community liaison by the Sünger Kent İzmir programme office preceded construction mobilisation by approximately six months. In the Xiamen context, the Yangfang community redevelopment programme demonstrates that co-designed sponge features — where residents participated in species selection for rain gardens — achieved higher long-term maintenance compliance than municipally mandated installations. The GIS-CMF recommends that stakeholder mapping be formally embedded in the Initiating process group of each pilot project, with a structured stakeholder register identifying each actor’s interests, influence, and preferred communication channel. For municipalities entering the steep learning curve segment, investing in community co-design at the earliest pilot sites is likely to yield compounding benefits: reduced change order frequency, higher plant survival rates attributable to community ownership, and stronger political support for programme scaling. Quantification of these stakeholder engagement benefits is acknowledged as a priority area for future empirical research as monitoring data from İzmir's pilot portfolio accumulate.

8.10. Conditions and Prerequisites for GIS-CMF Transferability

While the GIS-CMF is presented as transferable across contrasting geographical and institutional contexts, transferability is conditional rather than unconditional. Four prerequisite categories deserve explicit acknowledgement. First, data availability: the framework requires open or accessible spatial datasets including DEM of at least 30 m resolution, impervious surface maps validated against recent satellite imagery, and ecological constraint shapefiles; cities without open GIS data portals will face significant barriers to replicating the spatial analysis protocol at the level of rigour applied here. Second, ecological constraint mapping: the AHP-weighted MCA in Dimension 1 depends on verifiable ecological red line or equivalent protected-area designation data; in jurisdictions without formal spatial planning instruments of this type, a simplified constraint proxy based on remote sensing NDVI and hydrological soil group data is suggested as a minimum viable input. Third, institutional capacity requirements: deployment of the full GIS-CMF assumes availability of QGIS-trained GIS staff within the implementing organisation and familiarity with SWMM or equivalent hydrological modelling software; cities with limited in-house technical capacity may require an initial capacity-building investment before the framework can be operated independently. Fourth, GIS expertise and software infrastructure: cloud-based alternatives to desktop QGIS — such as QGIS Cloud or Google Earth Engine — can lower the entry barrier for smaller municipalities, though the spatial analysis outputs should be validated by a qualified GIS practitioner before informing investment decisions. Practitioners applying the GIS-CMF outside the studied contexts are encouraged to treat the quantitative parameters — AHP weights, PERT contingency ranges, and AVCR targets — as starting points for local recalibration rather than directly transferable benchmarks.

9. DISCUSSION

This study has suggested that GIS-based spatial analysis is not only a useful support tool for sponge city construction management but also the indispensable quantitative backbone without which site selection, scheduling and quality targeting lose their rigorous foundation. The spatial priority index derived in Dimension 1 provides a defensible, reproducible basis for resource allocation that goes beyond previous descriptive GIS applications in sponge city planning, reinforced by Moran's I analysis confirming the statistical significance of impervious surface hotspots. Although field validation remains essential, the SWMM-based hydrological projections for İzmir sub-catchments presented in Table 2 points out a model-suggested potential improvement in the range of 15-25 percentage points in AVCR, subject to field validation namely a meaningful planning-level advance,

The climate scenario analysis highlights a risk that current sponge city quality standards do not adequately examine. Under SSP2-4.5, the 10-year design storm intensity at İzmir is projected to increase by approximately 12% by 2050, which would reduce the effective

AVCR of fixed LID configurations by approximately 8-10 percentage points relative to historical calibration. This implies that sponge city design should incorporate a climate safety margin, either through upward revision of LID coverage targets or by the aid of modular design that can be retrofitted as climate projections are refined.

In addition to the advantageous features, it should be noted that there are several limitations. First, the SWMM simulations for İzmir are parameter-extrapolated rather than directly calibrated to long-term gauge records; NSE values of 0.71–0.78 fall below the 0.80 threshold recommended for design-level applications. Second, the Antalya case study is introduced as a qualitative reference based on published programme documents and does not receive the same depth of spatial analysis applied to İzmir and Xiamen. Third, the GIS-CMF principles are derived from two primary cases, limiting their generalizability. Fourth, all İzmir AVCR and peak flow reduction values reported in this study are SWMM model projections, not measured outcomes. Fifth, the use of SRTM 30 m DEM may miss fine-scale drainage features in dense urban areas; validation against higher-resolution LiDAR data is recommended before applying this methodology to detailed design decisions.

The findings of this study gain further depth when considered alongside the broader co-benefits and systemic challenges documented in the sponge city literature. Beyond runoff capture, green stormwater infrastructure in Chinese sponge city programmes has been shown to generate measurable carbon reduction benefits [43, 44] and multi-dimensional ecosystem services including water quality improvement, urban heat island attenuation, and biodiversity support co-benefits that are not captured by AVCR metrics alone and that strengthen the case for LID investment in emerging programmes such as İzmir's and Integrated assessments confirm that green infrastructure outperforms grey alternatives in flood mitigation cost-effectiveness when these ecosystem benefits are monetized alongside hydraulic performance [48, 49]. At the same time, the compound pressure of urbanization and climate change on urban flood volumes is well established [50], and a decade of implementation experience across China's pilot cities has revealed persistent institutional and technical challenges — including grey-green integration gaps and performance variability under extreme events — that temper optimism about rapid programme scaling [43, 51]. Recognizing these limitations is essential for construction project managers entering the steep segment of the learning curve: replicable performance gains require not only technically sound GIS-CMF application but also deliberate co-benefit accounting and honest assessment of boundary conditions under which LID configurations may underperform.

These considerations together strengthen the cautious, uncertainty-bounded framing adopted presented in this study. The opportunities that sponge city construction presents for cities at different stages of institutional maturity are real, but so are the structural difficulties [43, 51] and the gap between model-projected performance and field-validated outcomes whether in hydrology [48], carbon accounting [44], or ecosystem service delivery [49] accentuates the validation critical prerequisite embedded in the GIS-CMF's quality management dimension. It is precisely this gap that the transferable principles derived in Section 8 are designed to bridge, by embedding prospective monitoring, adaptive design triggers, and third-party verification as non-negotiable programme obligations rather than optional add-ons. The following section draws these threads together into conclusions examined to construction project managers, urban policymakers, and researchers seeking to operationalize GIS-based frameworks for nature-based urban infrastructure under institutional and climatic uncertainty.

10. CONCLUSIONS

This paper has developed and comparatively validated a GIS-based Construction Management Framework for sponge city infrastructure under ecological and spatial constraints, with three substantive advances over prior work: (1) transparent, reproducible spatial analysis protocols with full data source documentation; (2) SWMM-based hydrological performance projections for İzmir pilot catchments with Monte Carlo uncertainty quantification; and (3) institutional comparison through learning curve and barrier analysis frameworks that explicitly respect the scale asymmetry between the two primary cases. The four research questions were satisfied but needs to be improved in the future projects. Our research puts forward that:

-RQ1: Spatial-ecological overlays substantially reshape site rankings, disqualifying approximately 31% of İzmir and 37% of Xiamen metropolitan areas as primary intervention zones.

-RQ2: SWMM simulated estimates indicate a model-suggested potential improvement in the range of 15–25 percentage points in AVCR under current LID configurations, subject to field validation — well below China's 70% national standard but meaningful at planning level.

-RQ3: The regulatory framework is the dominant determinant of implementation velocity; learning curve analysis suggests unit delivery costs could fall by 50–60% once a 40–50 project portfolio is established.

-RQ4: Eight GIS-CMF principles are derived for construction project managers and these principles are presented as applicable guidelines rather than universally generalisable rules, because their empirical grounding is strongest for the İzmir–Xiamen comparison and requires contextual adaptation for other settings. Specific quantitative parameters (e.g., learning rates, cost bands, confidence intervals) should be recalibrated locally before application outside the studied cases

Türkiye's emerging sponge city experience exemplifies a critical juncture that many countries will face as they begin to scale nature-based urban water management. The GIS-CMF proposed here, with its transparent methodology and quantified uncertainty bounds, provides the analytical infrastructure for evidence-based national policy development.

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