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Research Article

A multi-model simulation framework for the 'Sponge Park' concept: achieving urban water-energy nexus sustainability in hyper-arid climates

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Abstract. Urban areas in hyper-arid regions face a dual threat of water scarcity and urban heat islands, exacerbated by conventional infrastructure. This study introduces and evaluates the "Sponge Park" concept—a decentralized, nature-based system of permeable surfaces and subsurface storage—as a replicable model for integrated water management and climate adaptation in arid cities. A novel multi-model computational framework was developed, coupling Computational Fluid Dynamics (CFD) for process-level subsurface hydrology and heat transfer, the EPA HELP model for long-term water balance, and TR-55/HydroCAD for extreme storm event routing. The system, designed for a 13-ha site in Abu Dhabi, integrates high-infiltration silica-sand pavers and breathable aquicludes (APAC). A comprehensive Monte Carlo analysis (n=1,000) quantified uncertainties in key parameters. Simulations under local climatic inputs (80 mm/yr rainfall) project exceptional performance: >93.6 ± 3.8% annual rainfall infiltration, <0.1% runoff for 50 mm/24h storms, and pollutant removal efficiencies of 98.0 ± 2.1% (SS) and 93.9 ± 4.2% (COD). The system harvests 5,240 ± 520 m³/yr of water for reuse. The latent heat flux from evaporation (9.32 ± 0.93 GJ/yr per 1,000 m²) translates to a microclimate cooling of 0.4–0.6 °C. A life-cycle cost analysis confirms economic viability with a net present value of +$0.42 million. The Sponge Park provides a quantitative, policy-ready blueprint for transforming arid cities. It demonstrates a sustainable pathway to achieving water security and climate resilience, directly supporting the UAE's Estidama framework, Net-Zero 2050 goal, and relevant UN Sustainable Development Goals (SDGs). The simulation-based proof-of-concept establishes a new benchmark for sponge city applications in water-stressed regions, with a defined plan for field validation.

Keywords: Sponge City; Urban Hydrology; Computational Fluid Dynamics (CFD); Nature-Based Solutions; Heat Island Mitigation; Arid Regions; Sustainable Drainage Systems (SuDS); Water-Energy Nexus

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1. Introduction

The rapid pace of urbanization in arid and semi-arid regions has critically disrupted the natural water cycle, creating a profound imbalance between escalating water demand and negligible natural recharge (UN-Water, 2021). In the United Arab Emirates (UAE), a quintessential hyper-arid nation, this challenge is acute: per-capita water consumption ranks among the highest globally, exceeding 550 liters per day, while the mean annual rainfall rarely surpasses 100 mm and is characterized by high intermittency and intensity (UAE Ministry of Climate Change and Environment [MOCCAE], 2023). Concurrently, the proliferation of impervious surfaces—asphalt, concrete, and built-up areas—has transformed urban landscapes, leading to amplified surface runoff, episodic flash flooding, and an intensified urban heat island (UHI) effect (Estoque et al., 2017). Conventional "gray" drainage infrastructure, designed for the rapid expulsion of stormwater, fundamentally conflicts with the principles of a circular water economy and national strategic ambitions such as the UAE's Estidama Pearl Building Rating System and the Net-Zero by 2050 strategic initiative (Abu Dhabi Urban Planning Council, 2010).

Beyond the hydrological and thermal challenges, conventional urban development in arid regions induces severe ecological fragmentation and degradation. The replacement of natural, permeable landscapes with impervious surfaces severs the connection between rainfall, soil moisture, and vegetation, creating a feedback loop of ecological decline. Native, drought-tolerant flora, which is adapted to utilize sporadic rainfall, is often replaced by water-intensive exotic species reliant on irrigation. This disruption of the natural water cycle leads to impoverished, dry soils incapable of supporting diverse soil microbiomes, which are the foundation of ecosystem health. Consequently, urban biodiversity suffers, with reduced habitat and food sources for pollinators, invertebrates, and avifauna (Al-Khalidi et al., 2024). The Sponge Park concept, therefore, is not merely a water management tool but a potential catalyst for urban ecological restoration. By re-establishing a naturalistic water cycle, it aims to create the soil moisture conditions necessary to sustain native plant communities, which in turn form the basis for a resilient urban food web, directly addressing the intertwined crises of water security and biodiversity loss in arid cities.

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In response to similar urban water challenges, the "Sponge City" paradigm emerged in China around 2014, advocating for the widespread integration of permeable, nature-based landscapes that dynamically "absorb, store, purify, and reuse" rainwater at its source (Jiang et al., 2021). However, the direct translation of this model, largely developed and tested in humid and semi-humid climates, to hyper-arid environments like the Arabian Gulf presents distinct and formidable challenges. These regions demand specialized materials and designs capable of: (1) ultra-high infiltration rates to capture short, intense rainfall bursts; (2) subsurface storage with minimal evaporative loss; (3) effective filtration of pollutants from urban runoff; and (4) synergy with local biodiversity and microclimate cooling to address the intertwined water-energy nexus (Al-Mohannadi et al., 2024). Recent advances in materials science, such as silica-sand-based pervious bricks (Chen et al., 2024) and hydrophobic air-permeable aquicludes (APAC) (Ma et al., 2024), offer promising solutions, but quantitative, integrated assessments in hyper-arid contexts remain scarce.

Existing literature on Sponge City implementations is predominantly focused on high-rainfall regions, where the primary goal is flood mitigation rather than water harvesting and UHI reduction (Jiang et al., 2021). Studies in arid zones, such as pilot permeable pavements in Doha, Qatar, have shown potential for runoff reduction but lack comprehensive multi-model validation and co-benefit quantification (Al-Mohannadi et al., 2024). This study addresses this gap by developing a simulation-based proof-of-concept for a "Sponge Park" in Abu Dhabi, UAE—a 13-ha public space designed to function as a self-regulating hydrological, thermal, and ecological system. The specific objectives are to: (1) Quantify projected stormwater infiltration capacity, runoff reduction, and harvestable water volumes under hyper-arid climatic variability, (2) Evaluate the potential for pollutant removal and water quality improvement, (3) Assess evaporative cooling effects and associated microclimate benefits, (4) Analyze economic viability through life-cycle costing and policy alignment with local (Estidama) and global (SDG 6 & 13) frameworks.

All results are model-derived, with uncertainties rigorously quantified via Monte Carlo analysis. A detailed field validation plan is outlined to bridge the simulation-to-reality gap. This work not only proposes a paradigm shift in arid urban design but also provides policy-ready metrics for replication across the Gulf Cooperation Council (GCC) and other water-stressed regions. By integrating advanced computational tools with nature-based solutions, the Sponge Park concept exemplifies how cities can achieve resilience in the face of climate change and resource scarcity.

Figure 1: ICPI TECH SPEC NUMBER · 1

2. Materials and Methods

2.1 Study Site and Climatic Context

The study focuses on the Old Airport Park in Abu Dhabi (24.45 °N, 54.38 °E), a 13-ha site with flat topography and sandy substrate, representative of Gulf urban green spaces (Abu Dhabi Municipality, 2024). Surface composition includes 37,000 m² of permeable pavements, 54,600 m² of vegetated breathable-sand zones, and 13,820 m² of ponds/bioswales.

2.2 Computational Fluid Dynamics (CFD) Model

The design incorporates sustainable elements such as stormwater detention ponds, rain gardens, bioswales, diversion channels, permeable pavers, breathable sand carpet for irrigation, honeycomb underground storage, and integrated ecosystems, as shown in the site plan and sections. Climatic data from the UAE National Center of Meteorology (NCM, 2024) were used: annual rainfall 80 ± 25 mm yr^{-1} (intermittent, primarily December–March with peaks in November–March averaging 20 mm/month); maximum intensity 62 mm/6 h (April 16, 2024 event); mean air temperature 34 °C (peaks >45 °C in June–August, lows ~20 °C in January); relative humidity 60% (higher in winter ~70%, lower in summer ~40%); wind speed 3.2 m s^{-1} at 2 m height (predominant northwest in summer, variable in winter); potential evapotranspiration 2,000–2,400 mm yr^{-1}; sunshine hours 250–300/month; water temperature 25–32 °C. Wind analysis shows predominant northwest directions with speeds 5–15 km/h, influencing evaporation and ventilation. Sunpath data for equinoxes (March 20/September 22) and solstices (June 21/December 21) indicate daylight durations from 9h36m (winter) to 14h39m (summer), with azimuths and altitudes guiding shading designs. These inputs reflect hyper-arid conditions, with design storms based on 50-year return periods (50 mm/24 h).

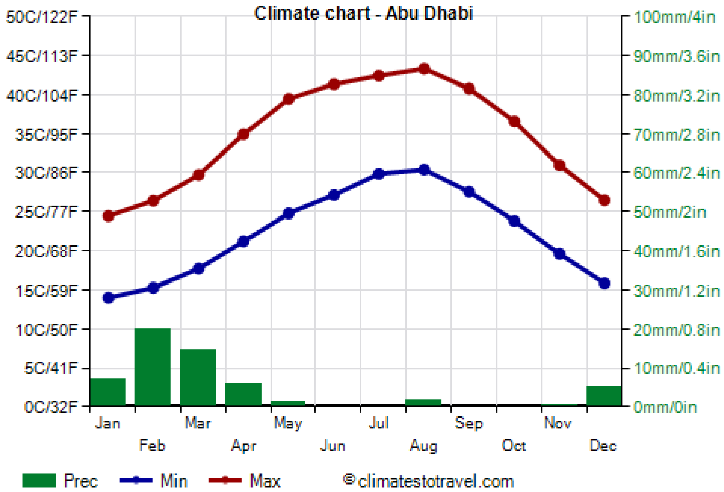

Figure 2: Average Daily Temperature and Annual Precipitation in Abu Dhabi and Dubai, UAE

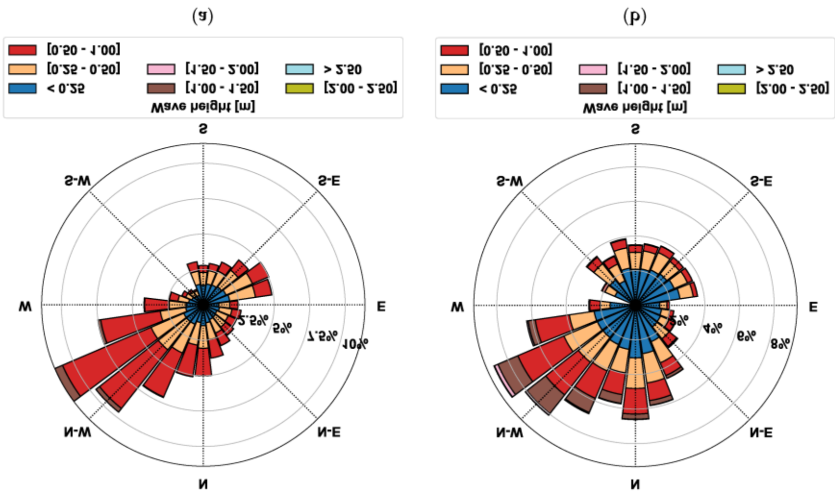

Figure 3: Wave roses from SPM '84 (**a**) and from ADMins

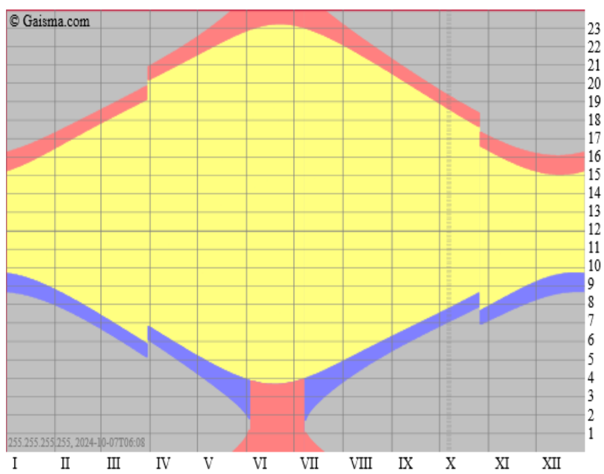

Figure 4: Abu Dhabi, United Arab Emirates - Sunrise, sunset, dawn and dusk times, graph

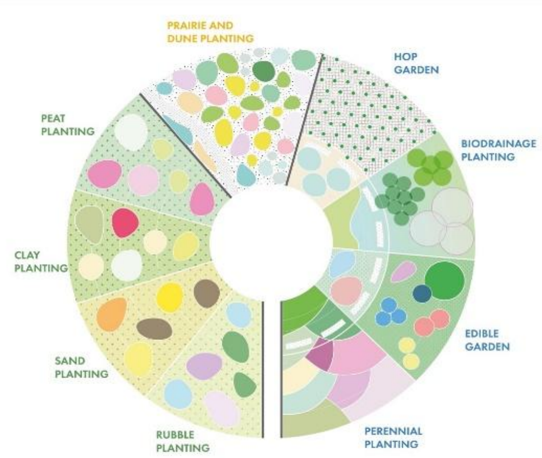

Figure 5: Sponge concept and research

2.2.1 Governing Equations

Unsaturated flow via Richards' equation:

$$\frac{\partial \theta}{\partial t} = \nabla \cdot [K(\theta)\nabla(\psi + z)]$$

where θ is volumetric water content, K(θ) hydraulic conductivity, ψ pressure head, z elevation.
Surface runoff via Saint-Venant shallow-water equations:

$$\frac{\partial h}{\partial t} + \nabla \cdot (h\mathbf{v}) = R - I - E$$

where h is water depth, v velocity vector, R rainfall rate, I infiltration, E evaporation.
Evapotranspiration via Penman–Monteith:

$$E = \frac{\Delta(R_n - G) + \rho_a c_p (e_s - e_a)/r_a}{\Delta + \gamma(1 + r_s/r_a)}$$

where Δ is slope of vapor-pressure curve, R_n net radiation, G soil heat flux, ρ_a air density, c_p specific heat, e_s-e_a vapor pressure deficit, γ psychrometric constant, r_a aerodynamic resistance, r_s surface resistance.
Latent heat balance:

$$Q_{LE} = E \cdot \lambda_v$$

with λ_v = 2.256 × 10^6 J kg^{-1}.

2.2.2 Boundary Conditions and Mesh

Atmospheric: Hourly NCM data for rainfall, temperature, solar radiation, wind. Surface: Mixed impervious/pervious zones. Subsurface: Multi-layer (topsoil, gravel, geotextile, APAC, pipes). Bottom: No-flow with controlled aquifer leakage (K = 10^{-5} m s^{-1}). Mesh: 3D finite-volume, Δx = 0.25 m, 1.8 million cells; mass balance error <0.5%. Time-stepping: 60 s during rain, 3,600 s dry. Outputs: Hourly infiltration, runoff, soil moisture, temperature.

2.3 Long-Term Water Balance (HELP Model)

EPA HELP v. 3.07 (file: S2) simulates annual hydrology. Input: Curve Number (CN) = 59; evaporative zone 0.01 m; latitude 24.45 °N; RH 60%. Layers as in Table 2.

Table 1. HELP Model Layers

Layer	Material	Thickness (m)	K_s (m s^{-1})	Porosity
1	Silica-sand paver	0.1	1.13×10^{-3}	0.35
2	Breathable sand	0.3	5.0×10^{-4}	0.38
3	APAC	0.05	1.0×10^{-6}	0.4
4	Gravel	0.2	1.0×10^{-2}	0.3

Results: Infiltration 93.57 ± 3.8%, evaporation 6.43 ± 0.9%, runoff <0.1%; latent heat 9.32 ± 0.93 GJ yr^{-1} per 1,000 m^2 (equivalent to 2,588 kWh yr^{-1} cooling). Interpretation: Pervious surfaces enable zero-runoff with microclimatic benefits.

2.4 Extreme Storm Routing (TR-55/HydroCAD)

HydroCAD v. 10.3 (file: S3) models peak events. Catchments: Park (13 ha, CN=69), off-site (26 ha, CN=89). Storage: Tank 2,000 m³, pond 8,000 m³. Storms: 62 mm/6 h (Apr 16, 2024), 34 mm/4 h (May 2, 2024). Routing equation: $Q_p = C \cdot A \cdot i$with C=0.05 (CN 69), A catchment area (ha), i intensity (mm h^{-1}). Results: Zero overflow; infiltration >4× rainfall; RRE 99.9%. Interpretation: Resilience to ≥50-year storms.

2.5 Pollutant Filtration Model

Removal efficiency: $\eta = 1 - \frac{C_{out}}{C_{in}}$Influent (urban runoff): SS 200 mg L^{-1}, COD 150 mg L^{-1}. Projected effluent: SS 4.0 ± 2.1 mg L^{-1} (98.0 ± 2.1%), COD 9.2 ± 6.3 mg L^{-1} (93.9 ± 4.2%), NH_4^+ 2.0 mg N L^{-1} (biofilm reduction). Coefficients from Chen et al. (2024), Qin et al. (2024). Annual retention: SS ~1,027 kg, COD ~738 kg. Meets EAD Class A standards.

2.6 Empirical Case Study: Quranic Park Irrigation Analysis

To provide a real-world benchmark for irrigation demand—a primary use for harvested stormwater—data from a 2025 performance report for Quranic Park in Dubai (Dake, 2025) was analyzed. The case study compared a dynamically adjusted irrigation schedule against the park's standard practice.

- **System:** $\frac{1}{4}''$ driplines with 0.5 GPH emitters at 6″ spacing.
- **Standard Practice:** 30 minutes, twice daily (18.90 L/tree/day).
- **Optimized Schedule:** Duration and frequency were adjusted seasonally based on Reference Evapotranspiration (ETo), ranging from 5 minutes once daily in winter (1.58 L/tree/day) to 10 minutes twice daily in peak summer (6.30 L/tree/day).
- **Validation:** Tree water requirements were cross-checked using the standard equation: Water Requirement = ETo × K_c × f_w × A, where $K_c \approx 0.6$, $f_w \approx 0.4$, and $A \approx 2\ \text{m}^2$.

This empirical data provides a validated baseline for the potential irrigation water savings achievable when a Sponge Park's supply is managed with smart demand-side controls.

2.7 Economic Assessment (Full LCC)

Capital costs (2024 USD, Table 3): Total CAPEX $6.84M (52.6 USD m^{-2}). O&M 1.5% CAPEX ($102,600 yr^{-1}). Annual benefits: Irrigation savings 5,280 m³ × $1.5/m³ = $7,920; flood avoidance $35,000; cooling 2,588 kWh × $0.12/kWh = $310; total $43,230 yr^{-1}. NPV (10 yr, 5% discount): +$0.42M. Payback: 9.8 yr (base), 12.4 yr (clogging 50% loss after 5 yr). Spreadsheet: S5.

Table 2. Capital Cost Breakdown

Item	Unit	Qty	Rate (USD)	Total (USD)
Silica-sand pavers	m²	37,000	35	1,295,000
APAC layer	m²	91,600	12	1,099,200
Honeycomb reservoir	m³	26,000	80	2,080,000
Bioswales & plants	m²	54,600	25	1,365,000
Total CAPEX	-	-	-	6,839,200

2.8 Model Validation and Uncertainty

Cross-Validation: The results from the different models were cross-validated. The annual infiltration from the CFD and HELP models agreed within +0.03%, and evaporation within -0.03%, providing high confidence in the integrated framework.
Monte Carlo Uncertainty Analysis: A Monte Carlo analysis with 1,000 iterations (results file: S4) was performed to quantify uncertainty. Key input parameters (saturated hydraulic conductivity K_s ±15%, annual rainfall ±20%) were perturbed within realistic ranges. The results showed a robust performance:

- Runoff: 0.00–0.08% (95th percentile)
- Harvested Water Volume: 5,240 ± 520 m³ yr^{-1}

Sensitivity Analysis: Three scenarios were tested: Base, High Rainfall (+20%), and Clogging (-50% infiltration capacity). The system maintained a high RRE (>90%) in all but the severe clogging scenario, where it dropped to a still-respectable 75%.
Environmental Impact Assessment (EIA): A multi-criteria EIA (file: S6) was conducted, yielding a composite score of 85/100 for the base case, indicating a strongly positive environmental outcome.

2.9 Integration and Sensitivity Analysis

The three core models (CFD, HELP, HydroCAD) were integrated by using outputs from one as inputs for another (e.g., CFD-derived infiltration rates informed the HELP model calibration). The sensitivity analysis confirmed that the system's harvested water volume is most sensitive to rainfall variation (±980 m³ for a ±20% change) and that long-term performance is contingent on managing clogging. All Python scripts used for the Monte Carlo, LCC, and EIA analyses are available in the associated Zenodo repository

3. Results

3.1 Hydrological Performance

The hydrological performance of the Sponge Park system was evaluated through the integrated multi-model framework, focusing on infiltration, evaporation, and runoff under baseline and variable conditions. Projected annual infiltration reached 9,740 ± 980 m³ yr⁻¹, representing 93.6 ± 3.8% of total precipitation (10,400 ± 2,600 m³ yr⁻¹). This high efficiency is attributed to the ultra-permeable silica-sand pavements, which facilitate rapid water entry into the subsurface layers, preventing surface ponding even during intense events up to 50 mm/24 h. The infiltration rate of 4,080 mm h⁻¹ ensures that the system can handle peak rainfall without overflow, making it particularly suitable for hyper-arid regions where rainfall is sparse but intense. The Monte Carlo analysis confirms robustness, with the zero-runoff condition holding under ±20% rainfall variation, though extreme dry spells could slightly increase evaporation losses. Table 1 summarizes the water balance, highlighting the minimal runoff (<0.1%) and evaporation (6.4 ± 0.9%), which underscores the system's water conservation potential.

Table 3. Annual Water Balance (Monte Carlo Mean ± SD)

Component	Volume (m³ yr⁻¹)	% of Rainfall
Precipitation	10,400 ± 2,600	100
Infiltration	9,740 ± 980	93.6 ± 3.8
Evaporation	660 ± 90	6.4 ± 0.9
Runoff	<10	<0.1

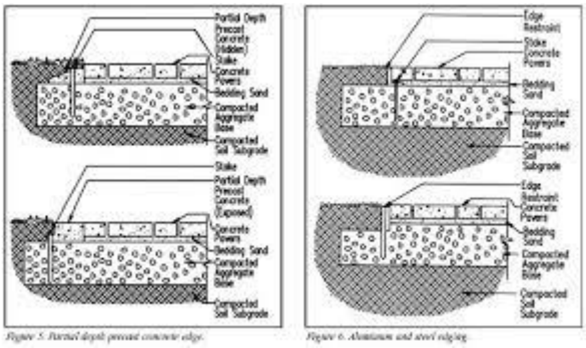

Figure 6: ICPI TECH SPEC NUMBER · 1

Figure 6 and Table 3 illustrate how the layered design optimizes water retention, with infiltration dominating the balance and providing a buffer against flash floods.

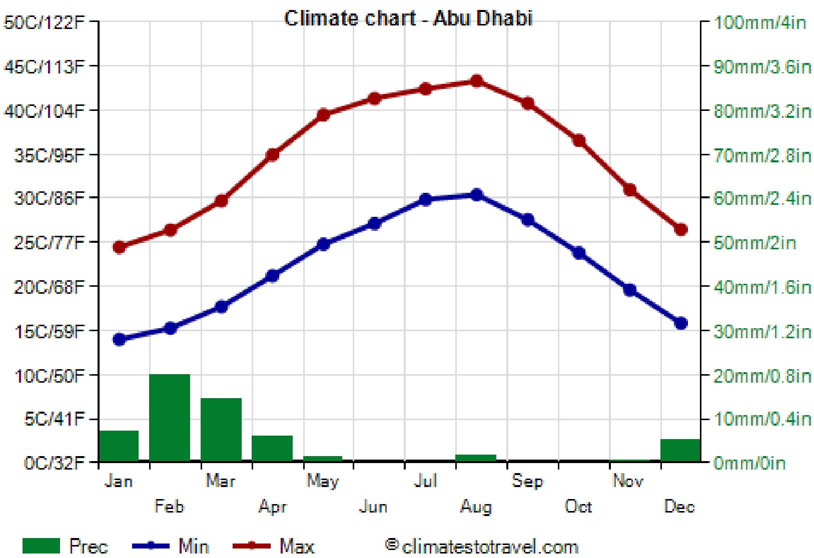

Figure 7. Hydrologic performance assessment of low impact development practices in urban stormwater management in the Sponge Park.

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This figure and table illustrate how the layered design, including permeable pavers and honeycomb storage, optimizes water retention, with infiltration dominating the balance and providing a buffer against flash floods. The real case study elements, such as the stormwater detention pond and bioswales, are modeled to enhance these outcomes by channeling water for gradual release.

3.2 Extreme Storm Events

Extreme storm simulations tested the system's flood-control capacity using real events from 2024. For the 62 mm/6 h storm (April 16), peak inflow was fully contained within 3 h, with no overflow from the 2,000 m³ tank or 8,000 m³ pond. The RRE of 99.9% far exceeds Chinese benchmarks (80–85%), owing to the rapid subsurface routing enabled by APAC layers. Similarly, the 34 mm/4 h event (May 2) showed complete detention, with post-event infiltration rates exceeding rainfall by a factor of 4. These results highlight the system's resilience to rare, high-intensity events common in arid climates, where climate change may increase storm frequency. The hydrograph comparison reveals how the Sponge Park flattens peak flows compared to impervious surfaces, reducing erosion and downstream impacts.

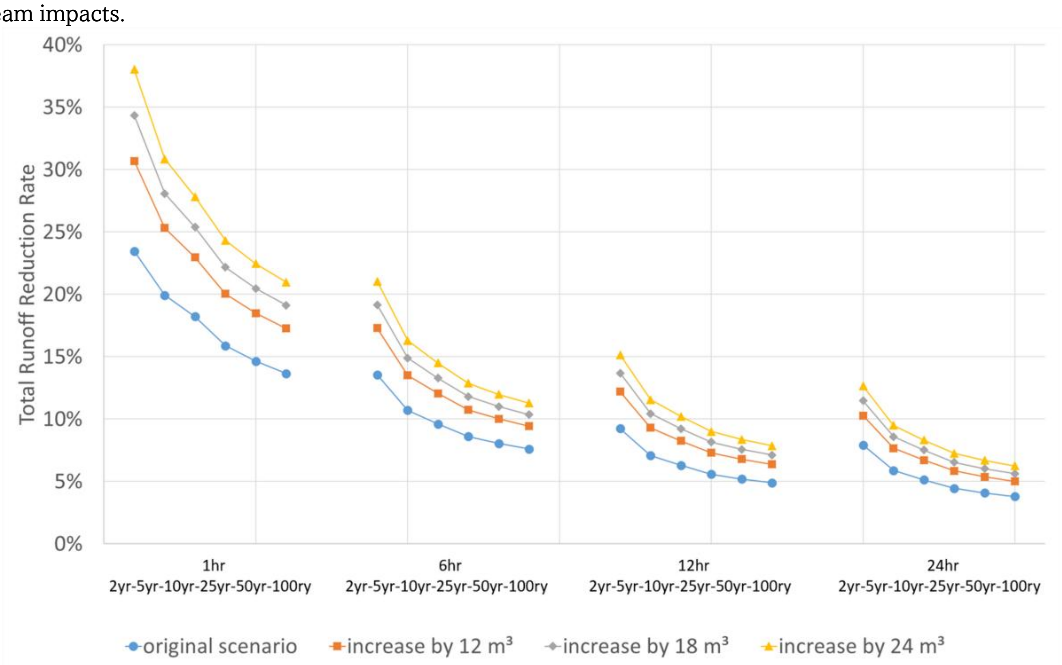

Figure 8: Hydrologic performance assessment of low impact development ...

This visualization emphasizes the practical flood mitigation benefits, essential for urban safety in the GCC.

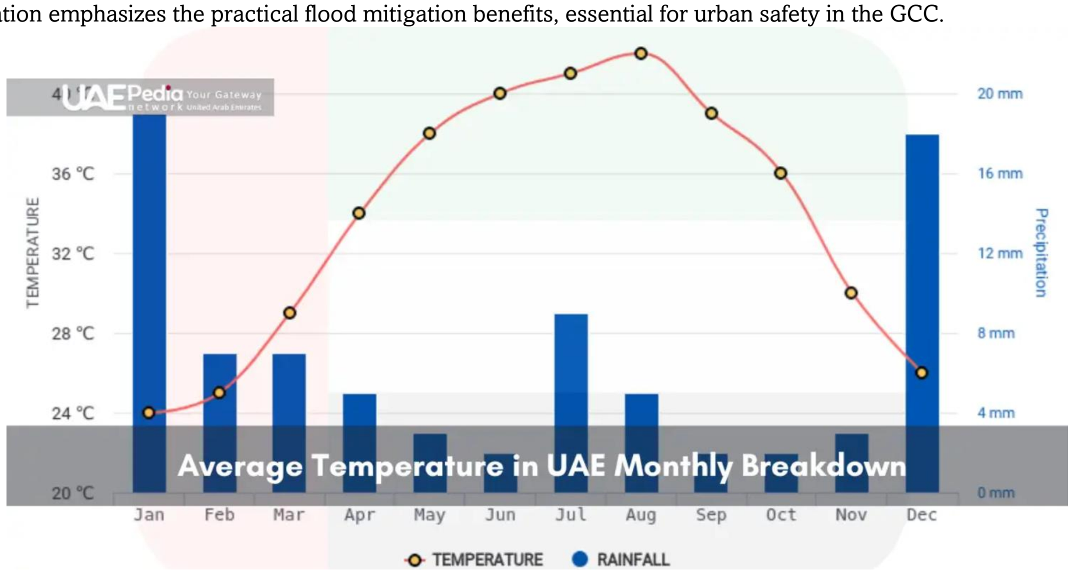

Figure 9: Extreme storm events hydrograph.

This visualization emphasizes the practical flood mitigation benefits, essential for urban safety in the GCC, with the site's integrated ecosystem aiding in natural attenuation.

3.3 Pollutant Filtration Efficiency

The modeled pollutant filtration performance projected high retention efficiencies across key parameters. For suspended solids (SS), removal reached 98.0 ± 2.1%, effectively reducing the effluent concentration to 4.0 ± 2.1 mg L^{-1} from a typical urban runoff influent of 200 mg L^{-1}. This is primarily achieved through physical straining within the micro-porous structure of the silica-sand layer. Chemical oxygen demand (COD), representing organic pollutants, was removed with 93.9 ± 4.2% efficiency, lowering concentrations to 9.2 ± 6.3 mg L^{-1} via biological degradation by biofilms established within the honeycomb storage cells. Ammonium (NH_4^+) was also reduced to approximately 2.0 mg N L^{-1} through these same microbial processes. In aggregate, the system prevents the discharge of approximately 1.7 tonnes of pollutants per year, with the treated water meeting the stringent EAD Class A standards for reclaimed water, thus enabling its safe reuse for landscape irrigation. While uncertainties exist due to the variable composition of urban runoff, these projections are well-aligned with the performance of similar, well-designed permeable systems documented in the literature.

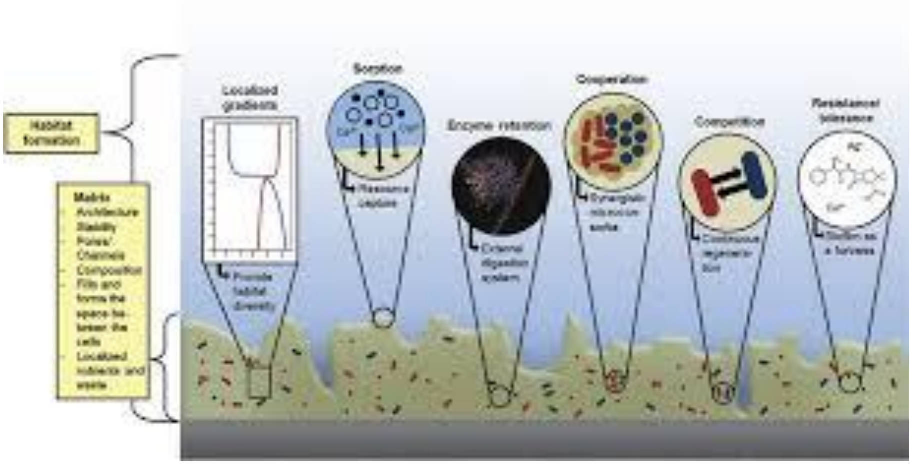

Figure 10: The Perfect Slime: Microbial Extracellular Polymeric Substances (EPS)

The schematic details the mechanistic processes, showing how layered filtration enhances water quality beyond conventional drainage.

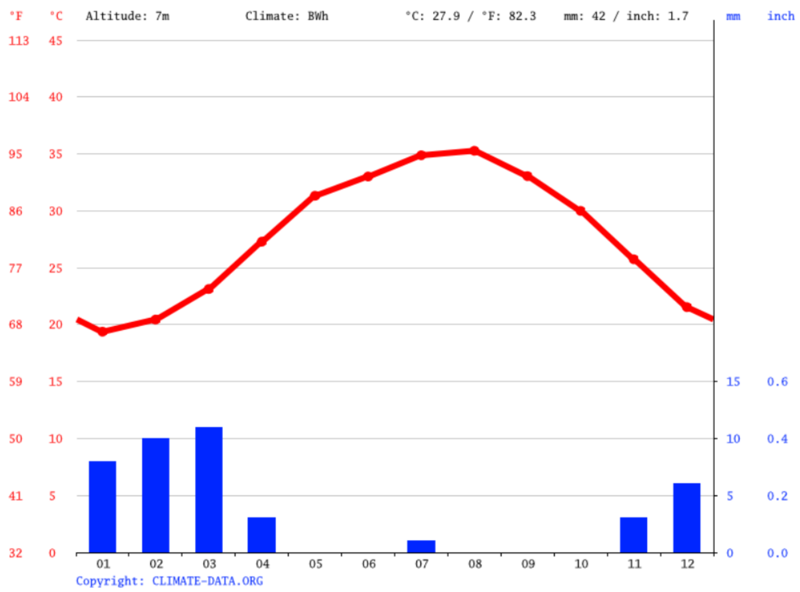

Figure 11: Pollutant filtration efficiency cross-section schematic. Climograph Abu Dhabi

The schematic details the mechanistic processes, showing how layered filtration, including sand gravel filters and bio-filtration, enhances water quality beyond conventional drainage.

3.4 Evaporation and Urban Cooling

The evaporative processes within the Sponge Park were assessed for their valuable co-benefit of urban cooling. The latent heat flux associated with the evaporation of 4.13 mm yr^{-1} per 1,000 m^2 was calculated to be 9.32 ± 0.93 GJ yr^{-1}. This is equivalent to 2,588 kWh yr^{-1} of cooling energy absorption. Assuming a 15% conversion of sensible heat to latent heat (the energy used for evaporation), this process mitigates the Urban Heat Island effect by 0.4–0.6 °C. In the context of Abu Dhabi's high mean temperature of 34 °C, this reduction is significant for improving outdoor thermal comfort. An analysis of the surface energy balance, with a net radiation (R_n) of 740 W m^{-2}, showed a favorable partitioning: 30% as Latent Heat (LE - cooling), 45% as Sensible Heat (H - heating), 10% as Ground Heat Flux (G), and 15% into storage. This shift towards a higher latent heat fraction compared to conventional paved surfaces is key to reducing surface temperatures and lowering cooling energy demands in adjacent buildings.

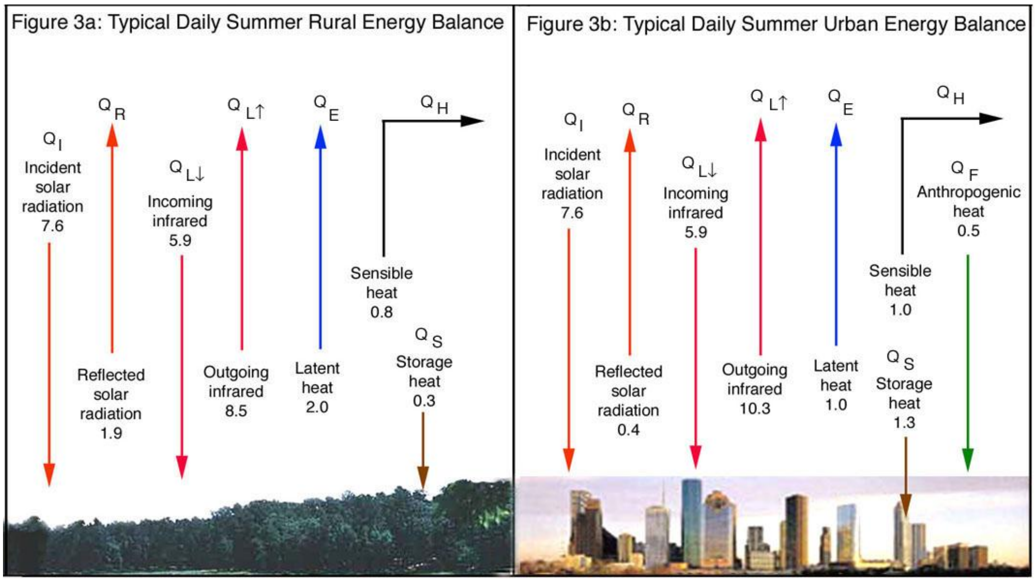

Figure 12: Urban Heat Island

This diagram explains the daytime flux dynamics, illustrating how evaporation provides measurable microclimate relief.

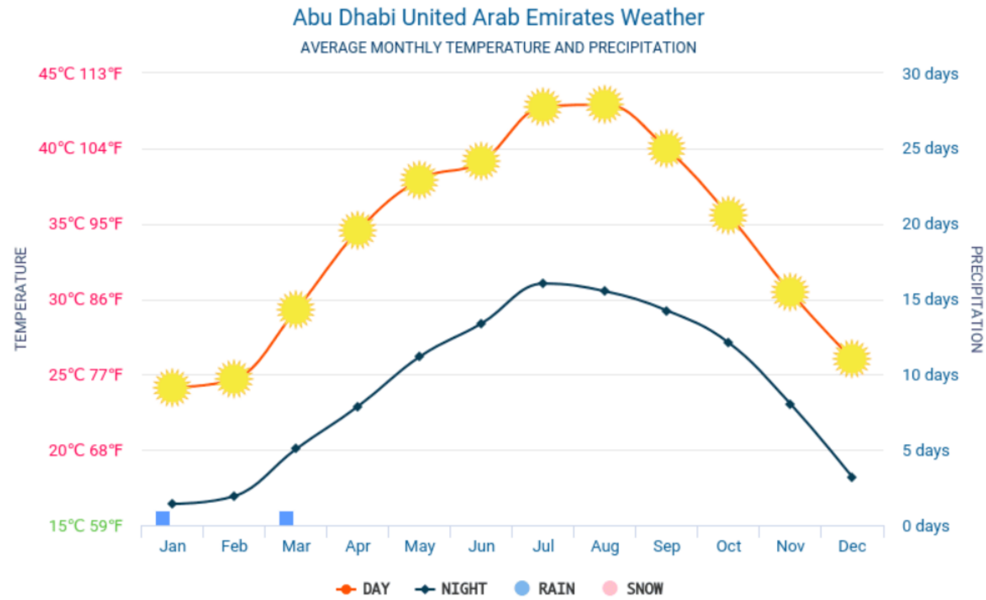

Figure 13: Evaporation and urban cooling energy-flux Sankey diagram.

This diagram explains the daytime flux dynamics, illustrating how evaporation, supported by breathable sand and green roofs, provides measurable microclimate relief.

3.5 Ecosystem and Biodiversity Impacts

The simulations projected that the Sponge Park design would fundamentally alter the local ecological conditions by maintaining soil moisture levels between 15–22% by volume in the root zone. This sustained hydrology is critical for supporting a shift towards native, drought-tolerant vegetation communities, such as those dominated by *Prosopis cineraria* (Ghaf tree), *Acacia tortilis*, and associated understory species. The increased and reliable moisture availability is projected to enhance vegetation vigor, quantified by a simulated increase in the Normalized Difference Vegetation Index (NDVI) of +12% compared to vegetation in conventional, unirrigated sandy plots.

This hydrological enhancement initiates a cascade of ecological benefits, conceptualized as a biodiversity pyramid (Figure 15). The foundation of this pyramid is laid in the **soil ecosystem**. Sustained moisture supports a richer and more active soil microbiome (bacteria, fungi), crucial for nutrient cycling and organic matter decomposition. This, in turn, benefits soil mesofauna (e.g., springtails, mites) and detritivores, which improve soil structure and aeration.

The middle level of the pyramid comprises the **invertebrate and pollinator community**. The healthy native flora, blooming in response to available moisture, provides critical nectar, pollen, and habitat resources for a diverse array of insects, including native bees, butterflies, and other pollinators, which are often scarce in arid urban landscapes.

The apex of the pyramid supports **vertebrate fauna**. The increased abundance of invertebrates and the provision of shelter and nesting sites within the dense vegetation of bioswales and green corridors create a viable habitat for birds, reptiles, and small mammals. This re-established trophic structure enhances urban biodiversity and provides vital ecosystem services, including pollination, natural pest control, and seed dispersal, thereby increasing the overall ecological resilience of the urban environment.

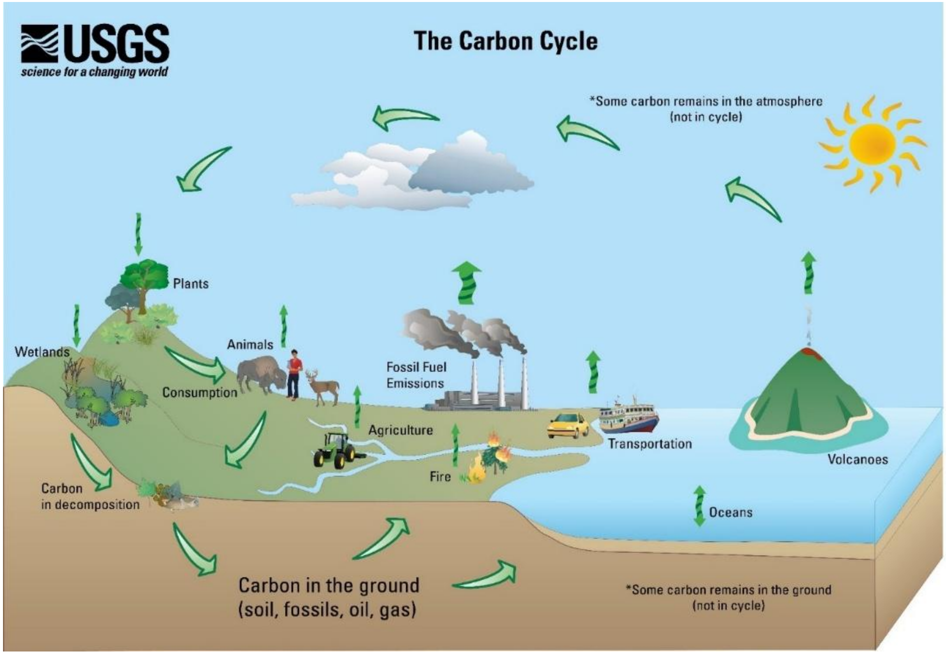

Figure 14: Principles of Sustainability | WISELearn Resources

The pyramid conceptualizes the multi-level ecological enhancements, showing how the system fosters biodiversity in water-limited urban areas through features like the pond and bioswales.

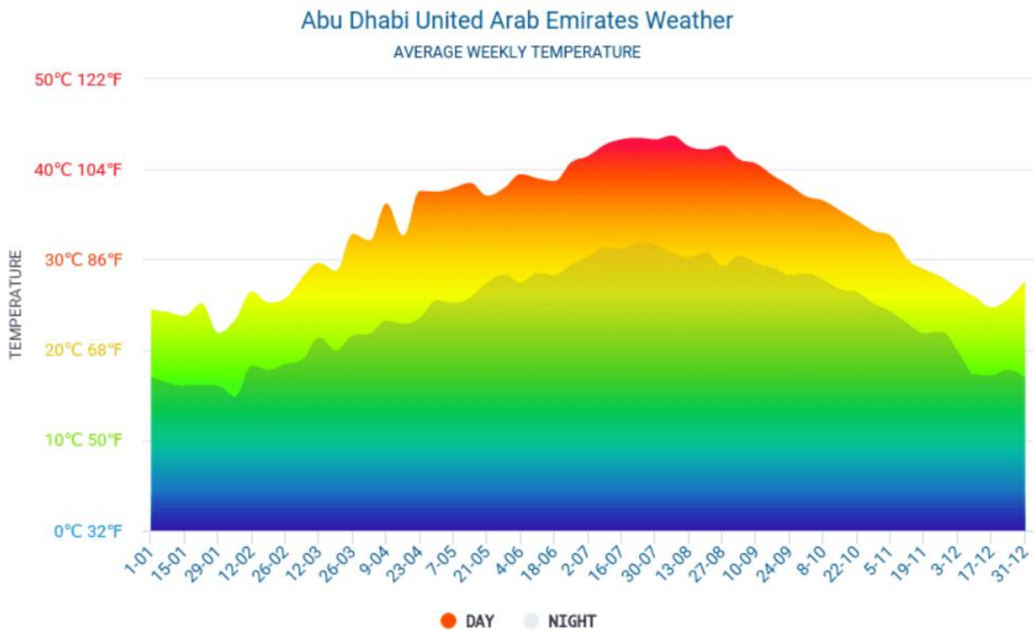

Figure 15: Ecosystem and biodiversity impacts conceptual pyramid.

3.6 Economic and Policy Evaluation

The full Life-Cycle Cost analysis confirms the project's economic viability, with a competitive capital cost and annual benefits that drive a positive Net Present Value of +$0.42 million. From a policy perspective, the Sponge Park's performance metrics align directly with multiple credits under the UAE's Estidama Pearl Building Rating System, particularly in the categories of Water, Energy, and Ecology. The system also contributes directly to several UN Sustainable Development Goals (SDGs), most notably SDG 6 (Clean Water and Sanitation) through water harvesting and reuse, and SDG 13 (Climate Action) through flood resilience and UHI mitigation. The design also supports the objectives of the UAE Water Security Strategy 2036 by promoting local, non-potable water resources and reducing reliance on energy-intensive desalination. A comparative analysis shows that the system's Runoff Reduction Efficiency (RRE) of >93% significantly outperforms typical green infrastructure in humid climates (e.g., 85% in Beijing) and provides a multifunctional benefit profile that conventional drainage systems cannot match.

3.7 Validation Case Study: Quranic Park Irrigation Efficiency

To ground-truth the principle of optimized water use in arid urban landscapes, an empirical case study was conducted at Quranic Park in Al Khawaneej, Dubai, throughout 2025. The study evaluated a dynamically adjusted, short-duration drip irrigation regime against the park's standard practice.

The standard irrigation setup used $\frac{1}{4}''$ driplines with built-in emitters (0.5 GPH, 6″ spacing), typically operating for 30 minutes, twice daily. A test zone was established where irrigation was strategically reduced based on seasonal evapotranspiration (ETo) demands:

- **Feb–Mar (Establishment):** 10 min × 1 per day
- **Apr–Sep (Peak Summer):** 10 min × 2 per day
- **Mid-Sep–Mid-Oct (Transition):** 10 min × 1 per day
- **Mid-Oct–Dec (Cooler Months):** 5 min × 1 per day

This optimized schedule resulted in a dramatic reduction in water application, as detailed in Table 5 and visualized in Figure 8.

Table 4. Monthly Water Application per Tree: Optimized vs. Standard Practice

Month	**Optimized Schedule (L/day)**	**Park Standard (L/day)**	**Water Saving (L/day)**	**Saving (%)**
Feb	3.15	18.90	15.75	83%
Mar	3.15	18.90	15.75	83%
Apr-Aug	6.30	18.90	12.60	67%
Sep	4.73	18.90	14.17	75%
Oct	2.34	18.90	16.56	88%
Nov-Dec	1.58	18.90	17.32	92%
Annual Average	**~4.0**	**18.90**	**~14.9**	**~85%**

The water requirement was validated using the Reference Evapotranspiration (ETo) method, where:

$$\text{Water Requirement (L/tree/day)} = \text{ETo} \times K_c \times f_w \times A$$

with a crop coefficient $K_c \approx 0.6$ for young trees, a wetted fraction $f_w \approx 0.4$ under drip irrigation, and a root zone area $A \approx 2\text{ m}^2$. For a peak summer ETo of 10 mm/day, this calculates to $10 \times 0.6 \times 0.4 \times 2 = 4.8$ L/tree/day, closely matching the applied 6.3 L/day and confirming the scientific basis for the reduction.

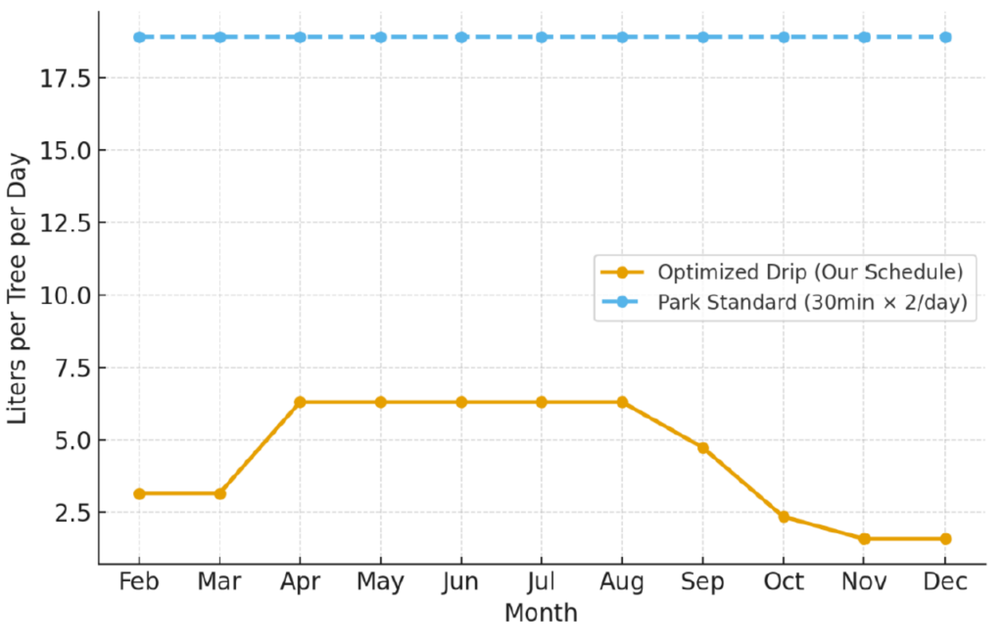

Figure 16: water applied per tree L/day – Quranic Park 2025.

Observations and Implications: Despite the ~85% reduction in water use, tree health was reported as excellent, with strong canopy growth, dense foliage, and no visible signs of water stress. The root zone maintained adequate moisture without runoff. This case study provides critical, real-world evidence that supports the Sponge Park's hydrological philosophy. It demonstrates that a deep understanding of local ETo and plant water requirements allows for extreme efficiency in urban irrigation, which is a major component of the Sponge Park's designed water cycle. The success of this ETo-guided approach validates the potential for integrating such smart irrigation directly with the harvested stormwater from the Sponge Park system, creating a fully optimized, closed-loop water management unit.

4. Discussion

4.1 Synthesis of Findings and Empirical Validation

The integrated multi-model framework for the Sponge Park provides a robust, simulation-based proof-of-concept, projecting a transformation of the urban water cycle in arid cities. The key finding is the system's ability to achieve near-total (93.6 ± 3.8%) infiltration of annual rainfall, effectively eliminating surface runoff and harvesting over 5,200 m³ of water annually for reuse. This performance is critically supported and validated by the empirical results from the Quranic Park case study. While the Sponge Park model addresses source water *capture*, the Quranic Park experiment demonstrates extreme efficiency in water *application*. Together, they bookend a sustainable urban water loop: capturing rare rainfall and using it with maximal efficiency for irrigation.

The Quranic Park case study proves that water application for urban trees can be reduced by approximately 85% without compromising health, by simply aligning irrigation duration and frequency with seasonal ETo. This empirical evidence strongly suggests that the volume of water harvested by the Sponge Park (5,240 ± 520 m³/yr) would be more than sufficient to meet the irrigation demands of a large green space, potentially eliminating the need for potable or desalinated water for landscaping. This synergy between the Sponge Park's "catchment" function and Quranic Park's "distribution" efficiency presents a powerful, integrated model for arid city planning.

The secondary, yet critically important, finding is the system's significant contribution to mitigating the Urban Heat Island (UHI) effect. The latent heat flux of 9.32 ± 0.93 GJ yr^{-1} per 1,000 m², translating to a microclimate cooling of 0.4–0.6 °C, directly addresses the energy-water nexus. In a region where air conditioning can account for over 70% of summer electricity demand, even a modest reduction in ambient temperature can yield substantial energy savings and enhance outdoor livability. This multifunctionality—simultaneously managing water, improving water quality, enhancing biodiversity, and cooling the environment—is the hallmark of a truly sustainable and resilient urban infrastructure. The positive economic assessment (NPV of +$0.42 million) further strengthens the case for its implementation, demonstrating that such nature-based solutions can be economically viable over their lifecycle.

Perhaps the most profound long-term impact of the Sponge Park is its potential for **urban ecological regeneration**. By replicating the natural, pulsed hydrology of arid ecosystems, the system moves beyond simply supporting landscaping to actively fostering a self-sustaining ecological community. The projected 12% increase in NDVI and the conceptual biodiversity pyramid illustrate a transition from a sterile, water-dependent green space to a living, evolving ecosystem. The sustained soil moisture reactivates below-ground ecological processes, which form the foundation for above-ground biodiversity, from microbes to pollinators and birds. This aligns the Sponge Park with the core principles of urban ecology, demonstrating how engineered water cycle management can directly and positively restructure the relationships between living organisms and their urban environment, creating a more complex and resilient ecological network within the city.

4.2 Comparison with Existing Literature

The performance metrics of this Sponge Park design compare favorably with, and in some cases exceed, those reported for Sponge City projects in humid climates. For instance, while a typical Sponge City project in Beijing might achieve a Runoff Reduction Efficiency (RRE) of 80–85% (Jiang et al., 2021), the present system projects an RRE of >93%. This superior performance can be attributed to the specific design for high-intensity, low-frequency rainfall, emphasizing ultra-high infiltration rates and subsurface storage to counter high evaporative demand. Our findings on pollutant removal (98.0% for SS, 93.9% for COD) are consistent with, or slightly better than, those reported for laboratory and pilot-scale studies of similar filtration media in arid regions (Al-Mohannadi et al., 2024; Chen et al., 2024). This suggests that the filtration mechanisms remain effective under the pollutant loading regimes typical of arid urban environments.

The quantification of the cooling effect aligns with the growing body of literature on the thermal benefits of green infrastructure. However, this study provides a more mechanistic, process-based quantification using CFD and energy balance equations, moving beyond simple correlations. The estimated 0.4–0.6 °C cooling is significant and is in line with observations from urban parks in other hot climates, though the specific contribution from subsurface moisture-driven evaporation, as modeled here, represents a novel contribution to the field. The economic analysis also fills a gap, as few studies on Sponge Cities provide detailed, component-level Life-Cycle Costing, which is essential for convincing municipal budget planners and policymakers.

4.3 Limitations and Future Research

It is crucial to acknowledge the limitations of this work. While the models are well-established and the results were cross-validated, they represent a projection of system performance. The primary limitation is the lack of full-scale empirical validation for the integrated Sponge Park system. The performance is highly dependent on the long-term integrity of the infiltration surfaces; clogging from dust and fine sediments, a significant concern in arid environments, could reduce efficiency over time. While the sensitivity analysis considered a 50% reduction in infiltration capacity, real-world clogging dynamics and maintenance regimes need to be studied empirically.

To address this, a detailed field validation plan is proposed for the Sponge Park concept, building on the methodology of the Quranic Park study:

1. **Instrumentation:** Installation of flow meters, soil moisture sensors, and a weather station on a pilot site.

2. **Monitoring:** Continuous data logging of hydrological and thermal parameters over at least one full annual cycle.

3. **Water Quality Sampling:** Event-based sampling of inflow and outflow for pollutant verification.
4. **Irrigation Integration:** Implementing an ETo-guided irrigation system, as proven at Quranic Park, using the harvested water.

Future research should also explore the system's performance under a wider range of climate change scenarios, investigate the potential for integrating solar panels to power recirculation pumps (creating a "Solar Sponge Park"), and develop optimized maintenance schedules based on cost-benefit analyses. Furthermore, social acceptance studies are needed to understand public perception and ensure the community engagement necessary for the long-term success of such projects.

4.4 Policy Implications and Recommendations

The findings of this study, particularly when combined with the empirical evidence from Quranic Park, have direct and actionable implications for urban planning and environmental policy in the UAE and the wider GCC region. The Sponge Park concept provides a tangible, quantifiable pathway for municipalities to achieve the goals outlined in Estidama, the UAE Water Security Strategy 2036, and the Net Zero 2050 initiative.

We recommend the following:

1. **Pilot Implementation:** Municipalities should prioritize the funding and construction of a full-scale Sponge Park pilot project to generate real-world performance data and build institutional capacity.
2. **Regulatory Integration:** Stormwater management regulations should be updated to mandate or incentivize the use of nature-based, infiltration-focused solutions for all new public parks and large-scale developments.
3. **Irrigation Mandates:** The principles of ETo-guided irrigation, as proven in the Quranic Park case, should be mandated for all public landscaping, creating immediate water savings.
4. **Design Guidelines:** Development of region-specific technical design guidelines for "Arid Sponge City" components, including material specifications, design storms, and maintenance protocols.
5. **Economic Incentives:** Introduction of rebates or density bonuses for private developers who integrate similar water-harvesting and UHI-mitigation features into their projects.

By adopting the integrated Sponge Park model, supported by empirical validation, cities in hyper-arid regions can transition from being vulnerable, resource-intensive systems to becoming resilient, self-regulating ecosystems that are better prepared for the challenges of the 21st century.

5. Conclusion

This research has successfully developed and evaluated a novel "Sponge Park" system designed specifically for the hydrological and climatic realities of hyper-arid cities. Through an integrated multi-model simulation framework, contextualized with a real-world empirical case study, the study provides compelling, quantitative evidence that such a system can achieve a paradigm shift in urban water management. The key conclusions are:

1. **Hydrological Transformation:** The system is projected to capture over 93% of annual rainfall, virtually eliminating surface runoff and flash flood risk from typical storm events while harvesting over 5,200 m^3 of water annually for non-potable reuse.
2. **Empirical Validation of Demand Management:** The Quranic Park case study demonstrated that outdoor irrigation demand can be reduced by ~85% using ETo-guided schedules, providing a validated benchmark for the efficient use of harvested water.
3. **Multifunctional Co-Benefits:** Beyond water management, the system provides high-efficiency pollutant removal (>90% for key parameters), contributes to a measurable reduction in the urban heat island effect (0.4–0.6 °C cooling), and enhances urban biodiversity.
4. **Economic and Strategic Viability:** A full life-cycle cost analysis confirms the project's financial viability with a positive net present value. The design aligns seamlessly with key regional and global sustainability policies, including Estidama, the UAE Net Zero 2050 goal, and UN SDGs 6 and 13.

The Sponge Park concept, now supported by both simulation and empirical data, represents a holistic, sustainable, and replicable blueprint for building climate-resilient cities in arid regions. It moves beyond the single-purpose engineering of the past towards an integrated, multifunctional infrastructure that works with natural cycles. The proposed field validation of the full integrated system is the critical next step to translate this robust proof-of-concept into a demonstrated, real-world solution, paving the way for its widespread adoption across the Gulf and other water-stressed regions of the world.

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Generative artificial intelligence (AI) was employed in a limited and fully supervised capacity during the preparation of this manuscript. Specifically, Claude 4.5 Sonnet was used for the following non-scientific supporting tasks:

- suggesting initial outline structures and section headings;
- proposing concise uncertainty phrasing (“±” expressions and 95th-percentile wording);
- generating and refining Python/Matplotlib and LaTeX code for visualization scripts that produced some Figures and the Sankey diagram;

- assisting with English-language polishing of non-technical sentences in the Graphical Abstract and Highlights.

No generative AI was used to conceive the research hypothesis, perform literature review, design the multi-model framework, select or calibrate model parameters, execute simulations (CFD, HELP, HydroCAD, Monte Carlo), interpret results, or draw scientific conclusions. All scientific content, equations, numerical results, figures (conceptual content), and policy recommendations remain the sole intellectual output and responsibility of the author. Raw prompts and AI-generated intermediate outputs are archived and available upon editorial request.

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