

Remote Monitoring of Water-Efficient Blue–Green Roofs Using Satellite-Derived Evapotranspiration in a Mediterranean Climate

Surveillance à distance de toitures bleu-vert économes en eau à l'aide de l'évapotranspiration dérivée de données satellitaires dans un climat méditerranéen

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RÉSUMÉ

Les villes des climats méditerranéens sont confrontées à une pénurie d'eau croissante, à un stress thermique accru et à des épisodes de pluie courts et intenses, tandis que l'adoption à grande échelle des toitures bleu-vert (BGR) reste limitée par les besoins en irrigation et l'absence de méthodes de suivi continu et fiables. Cette étude évalue une configuration de BGR économe en eau, dans laquelle un réservoir intégré à la toiture alimente le substrat par remontée capillaire, avec des apports saisonniers supplémentaires dimensionnés pour être comparables aux volumes de condensats produits sur site par les systèmes de climatisation. Le site expérimental du Technion (Haïfa, Israël) comprend deux parcelles identiques de 100 m² : une parcelle de référence utilisant une irrigation goutte-à-goutte conventionnelle en surface, et une parcelle test recevant l'eau directement dans la couche de stockage. Des observations météorologiques et hydrologiques haute résolution sont utilisées dans un cadre de bilan hydrique bi-couche (bleu-vert) afin de quantifier l'évapotranspiration (ET), la dynamique de stockage, les flux internes et la rétention des eaux pluviales sous une disponibilité en eau restreinte. Les images Sentinel-2 sont exploitées pour dériver des coefficients culturaux et de stress hydrique (Kc, Ks), ensuite utilisés pour estimer l'ET et assurer un suivi continu des performances et du stress hydrique à l'échelle de la toiture. Les résultats attendus visent à renforcer des approches pratiques et évolutives pour la conception et l'évaluation de systèmes BGR économes en eau dans des environnements urbains soumis à la sécheresse.

ABSTRACT

Cities in Mediterranean climates face increasing water scarcity, heat stress and short, intense rainfall events. At the same time, large-scale adoption of blue–green roofs (BGRs) is limited by irrigation demands and the lack of robust, continuous performance monitoring. This study evaluates a water-efficient BGR configuration in which a roof-level reservoir supplies water to the substrate by passive capillary rise, with seasonal supplemental inputs designed to be comparable to on-site air-conditioner condensate volumes. An experimental roof at the Technion (Haifa, Israel) comprises two identical 100 m² plots: a reference plot with conventional surface drip irrigation and a test plot receiving water into the storage layer. High-resolution meteorological and hydrological observations are used within a two-layer (blue–green) water-balance framework to quantify evapotranspiration (ET), storage dynamics, internal fluxes and stormwater retention under constrained water supply. Sentinel-2 satellite imagery is processed to derive crop and stress coefficients (Kc, Ks), which are then used to estimate ET and support continuous roof-scale performance and water-stress monitoring. The findings are expected to advance practical, scalable approaches for designing and evaluating water-efficient BGR systems in drought-prone urban environments.

KEYWORDS

blue-green roofs; evapotranspiration; capillary irrigation; stormwater retention; Remote sensing; Mediterranean climate.

1 INTRODUCTION

Cities in Mediterranean regions are increasingly affected by global climate change, urbanization, and population growth, leading to growing water scarcity, rising temperatures, and more frequent short, intense rainfall events alongside prolonged dry periods (Bellini et al., 2024). Blue-green roofs (BGRs) are established nature-based solutions that contribute to urban resilience via stormwater retention and peak attenuation, with co-benefits for urban heat mitigation, biodiversity, and energy savings (Vijayaraghavan, 2016). Adoption in hot and dry Mediterranean settings remains limited, although interest is growing, due to local barriers that constrain widespread implementation (Bellini et al., 2024). Two practical constraints occur. First, irrigation demand can be resource-intensive and costly. Second, monitoring BGRs remains a significant challenge. Routine inspections are labor-intensive and often limited by accessibility, while field-sensor networks are expensive to install and maintain. Consequently, many systems fall out of proper maintenance, and stakeholders hesitate to adopt BGRs. This study aims to address these barriers and support broader large-scale implementation.

To avoid plant stress and sustain function, many BGR schemes rely on extensive irrigation, which undermines resource efficiency where water is scarce (Schweitzer & Erell, 2014). A key objective is to determine the minimum irrigation required to maintain vegetation function and hydrologic performance under Mediterranean conditions. Therefore, a water-stressed design is needed. The approach utilizes the blue-roof reservoir to buffer dry spells and reuse stored water for irrigation of the green roof, selects substrates with sufficient capillarity and available water capacity, and employs drought-tolerant plant species suited to shallow soils. Passive capillary irrigation is a promising approach because stored water can be lifted from the blue layer by capillary rise, providing a self-regulated, energy-free moisture supply to the substrate, eliminating the need for complex irrigation infrastructure and reducing operational costs (Cirkel et al., 2018). During the dry summer period, minimal supplemental irrigation may be supplied from alternative on-site sources such as air-conditioner condensate, supporting a closed-loop and water-efficient operation (Ahmed, 2025). Despite this conceptual appeal, quantitative evidence under BGR operating conditions remains limited, and the operational thresholds defining the minimum water required to maintain performance are not yet well established.

A second barrier is scalable and reliable performance monitoring. Practice usually relies on visual inspections, which are essential but episodic and labor-intensive (Vijayaraghavan, 2016). While in-situ sensors provide high-quality data, their installation, maintenance, and replication across many roofs are costly and limit large-scale observability. Open-access satellite remote sensing (e.g., Landsat and Sentinel missions) offers a complementary and cost-effective approach for continuous monitoring. Yet, roof-scale application remains challenging due to spatial resolution, spectral mixing, and viewing geometry. Evapotranspiration (ET) serves as a central integrative variable linking vegetation condition, substrate moisture, and hydrological performance. Although ET monitoring using satellite imagery is well established in agricultural systems (Imtiaz et al., 2023), its application to blue-green roofs remains limited and technically demanding, underscoring the need for site calibration and the adaptation of remote-sensing approaches to urban roof environments.

This study evaluates a water-efficient BGR using passive capillary irrigation, examines whether condensate can meet dry-season water needs, and develops a continuous remote-monitoring approach to quantify hydrological performance through ET.

2 METHODS

2.1 Study site and experimental design

The study is conducted at the Technion, Haifa, Israel, a coastal city with a Mediterranean climate (Csa; Köppen Geiger classification) characterized by hot, dry summers, mild, wet winters, and short high-intensity rainfall events with annual rain of approximately 550 mm. The experimental roof is divided into two adjacent 100 m² plots with identical orientation and structural configuration. From bottom to top, the buildup includes a thin insulation and waterproofing layer, an 8.5 cm water storage module with a capacity of approximately 85 L m⁻², a geotextile separator layer, a lightweight substrate composed of about 20% composted organic matter and 80% inorganic aggregates such as perlite and crushed tuff, and vegetation of drought tolerant Sedum species suited to shallow soils. Plot A employs conventional surface drip irrigation. Plot B receives irrigation delivered directly into the water module, with moisture supplied to the substrate by capillary action only. Stored rainwater is used as the primary source. During summer, a minimal supplemental volume is supplied, targeted to match on site air conditioner condensate yield, to test whether this source can meet the vegetation's minimal water requirement without performance loss. An illustration of the experimental setup and layer sequence is shown in Figure 1.

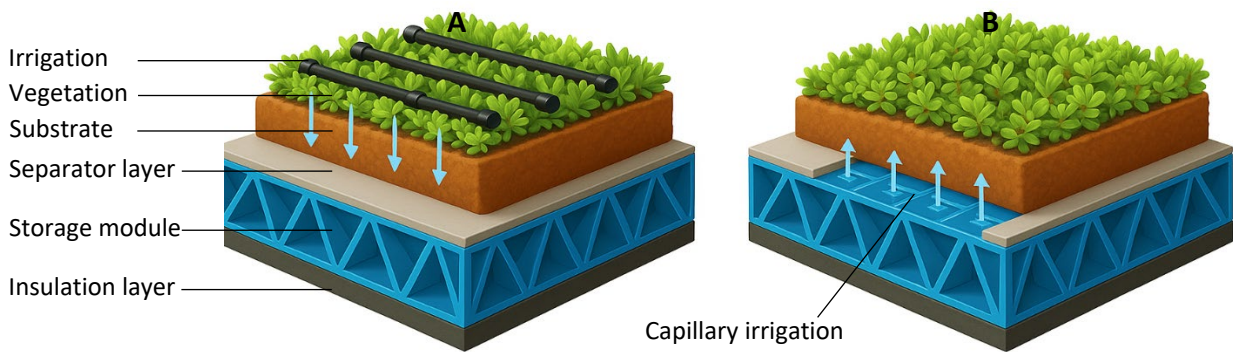


Figure 1: Experimental setup: Plot A (left) with conventional surface drip irrigation, and Plot B (right) with passive capillary irrigation drawing water from the blue-roof reservoir. Both plots have identical structure and vegetation layers.

Meteorological variables recorded on site include wind speed, rainfall, air temperature, and relative humidity. Hydrological data include plot outlet flow measured with flow meters. Substrate conditions are monitored using volumetric water-content and temperature sensors installed at the center of each plot. Irrigation input is metered separately for each plot. Sensor placement is mirrored between plots to ensure comparability. All data are logged every 10 minutes and transmitted via a cellular network for quality-controlled processing.

2.2 Modelling framework

A two-layer mass balance is applied to each plot, separating the green layer (substrate and vegetation) from the blue storage layer. The whole plot balance at time step t is described as follows:

$$S(t) = S(t-1) + P(t) + IR(t) + D(t) - ET(t) - Q_{out}(t) \quad (\text{Eq. 1})$$

where $S(t)$ is total water stored in the system, $P(t)$ is effective rainfall entering the plot, $IR(t)$ is irrigation input, $D(t)$ is dew (neglected), $ET(t)$ is actual evapotranspiration, and $Q_{out}(t)$ is measured outflow at the plot outlet. Since $S(t) = S_g(t) + S_b(t)$, adding the layer balances recovers (Eq. 1):

$$S_g(t) = S_g(t-1) + P(t) + IR(t) + D(t) + CR(t) - ET(t) - ID(t) \quad (\text{Eq. 2})$$

$$S_b(t) = S_b(t-1) + ID(t) - CR(t) - Q_{out}(t) \quad (\text{Eq. 3})$$

where S_g and S_b are the green and blue storages, $CR(t)$ is capillary rise from blue to green, and $ID(t)$ is internal drainage from green to blue. Reference evapotranspiration ET_0 is computed from on site meteorology using the FAO 56 Penman–Monteith method (Allen et al., 1998). Actual evapotranspiration is represented as:

$$ET(t) = ET_0(t) \cdot K_c(t) \cdot K_s(t) \quad (\text{Eq. 4})$$

2.3 Remote sensing

Satellite multispectral imagery (Sentinel-2; 10 m resolution, ~5-day revisit) is used to extend ground observations and enable continuous monitoring (Imtiaz et al., 2023). The imagery is atmospherically corrected, cloud and shadow-masked and clipped to the roof footprint to ensure accurate reflectance from the study plots only. Vegetation condition used for estimating the vegetation coefficient $K_{c,sat}$ is derived from the Normalized Difference Vegetation Index (NDVI), calibrated empirically against ground data collected on the plots. Water-stress conditions for the stress coefficient $K_{s,sat}$ are assessed using the Normalized Difference Moisture Index (NDMI), which is sensitive to canopy and surface moisture content. NDMI values are normalized between site-specific wet and dry reference states identified from soil-moisture measurements to obtain a satellite-based water stress factor. Satellite-based ET for continuous monitoring is estimated as:

$$ET_{sat} = ET_0 \cdot K_{c,sat} \cdot K_{s,sat} \quad (\text{Eq. 5})$$

and validated against ground-derived ET using split-sample analysis with RMSE and mean bias as evaluation metrics.

3 DISCUSSION

Field measurements will begin in January 2026, and the conference presentation will present analyses from the first six months of monitoring. The study evaluates whether a passive capillary irrigation system can sustain substrate moisture and vegetation vitality with reduced water input by utilizing the blue-roof reservoir. ET is used as an integrative measure linking water input, vegetation response, and hydrological performance. A second focus is operational monitoring. In practice, many assessments treat the crop and stress coefficients (K_c and K_s) as fixed for a given planting scheme, even though ET varies with weather, season, and plant condition. This simplification can bias estimates of retention, runoff coefficients, and peak attenuation, and it obscures maintenance needs when vegetation declines. By calibrating time-varying $K_{c,sat}$ and $K_{s,sat}$ from satellite indices and tying them to ground measurements, the approach provides a dynamic indicator of roof status that can inform irrigation adjustment, flag emerging stress, and improve event-scale runoff quantification for stormwater management. Key challenges relate mainly to the use of satellite imagery. The coarse 10 m resolution of Sentinel-2 means that a single pixel does not perfectly match the roof footprint, leading to mixed-pixel effects that can affect ET_{sat} accuracy. In addition, cloud cover occasionally limits data availability. At the conference, a method for isolating roof-specific reflectance from partial pixels will be presented, demonstrating how these constraints are mitigated to ensure reliable roof-scale monitoring and runoff estimation. Overall, this integrated framework marks an important step toward advancing large-scale implementation of BGR, demonstrating that combining low-maintenance, water-efficient irrigation with satellite-based monitoring can support resilient performance even in hot, drought-prone urban environments.

LIST OF REFERENCES

- Ahmed, H. M. (2025). Air Conditioning Condensate: A Potential Water Source for Irrigation. In E. AlDhaen, A. Braganza, A. Hamdan, & W. Chen (Eds.), *Business Sustainability with Artificial Intelligence (AI): Challenges and Opportunities: Volume 1* (pp. 1213–1223). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-71526-6_105
- Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration: Guidelines for computing crop water requirements* (No. 56; FAO Irrigation and Drainage Paper). Food and Agriculture Organization of the United Nations. <https://www.fao.org/3/x0490e/x0490e00.htm>
- Bellini, A., Bartoli, F., Kumbaric, A., Casalini, R., & Caneva, G. (2024). Evaluation of Mediterranean perennials for extensive green roofs in water-limited regions: A two-year experiment. *Ecological Engineering*, 209, 107399. <https://doi.org/10.1016/j.ecoleng.2024.107399>
- Cirkel, D. G., Voortman, B. R., Van Veen, T., & Bartholomeus, R. P. (2018). Evaporation from (Blue-)Green Roofs: Assessing the Benefits of a Storage and Capillary Irrigation System Based on Measurements and Modeling. *Water*, 10(9), 1253. <https://doi.org/10.3390/w10091253>
- Imtiaz, F., Farooque, A., Wang, X., Abbas, F., Afzaal, H., Esau, T., Acharya, B., & Zaman, Q. (2023). Mapping crop evapotranspiration with high-resolution imagery and meteorological data: Insights into sustainable agriculture in Prince Edward Island. *Frontiers in Remote Sensing*, 4. <https://doi.org/10.3389/frsen.2023.1274019>
- Schweitzer, O., & Erell, E. (2014). Evaluation of the energy performance and irrigation requirements of extensive green roofs in a water-scarce Mediterranean climate. *Energy and Buildings*, 68, 25–32. <https://doi.org/10.1016/j.enbuild.2013.09.012>
- Vijayaraghavan, K. (2016). Green roofs: A critical review on the role of components, benefits, limitations and trends. *Renewable and Sustainable Energy Reviews*, 57, 740–752. <https://doi.org/10.1016/j.rser.2015.12.119>