Benchmarking satellite-based evapotranspiration models with flux towers for agricultural water management

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Abstract: Accurate quantification of actual evapotranspiration (ETa) is fundamental for water balance assessment, irrigation planning and climate adaptation in intensively irrigated regions. Despite advances in remote sensing, large-scale ET estimation remains challenging due to uncertainties in biophysical drivers, input data quality and algorithm transferability across heterogeneous landscapes. While satellite-based products such as FAO WaPOR and the Surface Energy Balance Algorithm for Land (SEBAL) offer scalable monitoring solutions, their accuracy under local biophysical and management conditions remains insufficiently assessed.

This study provides the first comprehensive validation of satellite-derived ETa against direct eddy covariance (EC) flux measurements across contrasting agro-ecological zones of Pakistan. Four EC towers were deployed across representative irrigated system including Faisalabad (irrigated rice–wheat), Okara (mixed cropping), Rahim Yar Khan (hyper-arid cotton–wheat) and Chakwal (semi-arid rainfed). To reconcile spatial and temporal scales, innovative data modelling techniques were applied, including footprint-aware flux aggregation of high frequency EC fluxes measurements to provide consistent ground truth data for validating satellite-derived ET estimates. Daily and monthly ETa for 2024 were generated from WaPOR and a custom SEBAL model integrating Landsat 8 thermal/optical imagery with ERA5 climate forcing. Model performance was assessed using statistical indicators to capture both magnitude and temporal consistency.

Comparative analysis revealed strong advantages for SEBAL across most environments. SEBAL achieved R^2 values of 0.85–0.94 and RMSE of 6–12 mm/month, closely matching EC-measured latent heat fluxes and capturing seasonal crop water-use dynamics. In contrast, WaPOR, while providing continuous regional coverage, performed less reliably (R^2 = 0.30–0.55; RMSE = 21–49 mm/month), particularly in hyper-arid and heterogeneous settings where coarse inputs were unable to resolve local variability. At the semi-arid Chakwal site, both models showed higher uncertainty due to rainfed conditions, complex terrain and frequent cloud interference, emphasizing the need for adaptive modelling strategies.

These findings highlight two critical insights of global relevance: (i) operational products of actual ET like WaPOR, while valuable at regional to continental scales, require caution when applied in heterogeneous, water-limited environments; and (ii) physically based models such as SEBAL, when carefully parameterized with local climate and surface data, can provide robust and transferable estimates across a range of cropping systems and climates. The study demonstrates the added value of integrating high-resolution Landsat-driven SEBAL with flux-tower validation as a scalable pathway for ET monitoring in data-scarce agricultural systems. This illustrates how EC towers can serve as anchor sites for algorithm calibration, cross-sensor harmonization and fusion with emerging data sources of ET such as ECOSTRESS and Sentinel-2. By combining satellite observations with advanced data modelling and ground-based flux monitoring this work highlights operational strategies to enhance ET estimation for agricultural productivity assessment, crop water modelling, and climate-resilient water management.

Keywords: *Evapotranspiration, remote sensing, SEBAL, eddy covariance, agricultural water modelling*