Satellite-based water budgeting and seasonal groundwater stress assessment in Indus Basin using flux towers

Umar Waqas Liaqat[1], **Mohsin Hafeez**[1], **Habib Ullah Bodla**[1] **and Faris Ahmad**[1]

[1]*International Water Management Institute (IWMI), Pakistan*
Email: u.liaqat@cgiar.org

Abstract: Groundwater depletion is a growing challenge in irrigated agriculture worldwide, particularly in semi-arid regions where canal and rainfall supplies are insufficient to meet crop water requirements. Despite its critical importance, systematic monitoring of groundwater abstraction is limited in many large irrigation systems due to sparse hydrometeorological networks and fragmented data availability. This study develops a remote sensing–based water budgeting framework that integrates open-access Landsat products with field-based observations to quantify seasonal water balances and groundwater stress at both district and canal-command scales in the Indus Basin Irrigation System (IBIS) of Pakistan.

The approach combines phenology-based land use classification with the PySEBAL model to generate 30 m resolution actual evapotranspiration (ETa) estimates for the 2023–24 summer (Kharif) and winter (Rabi) seasons. To address temporal gaps in the Landsat record, we apply footprint-aware temporal interpolation and meteorologically scaled gap-filling so that ETa fields represent continuous seasonal dynamics relevant for water accounting. Modelled ETa was rigorously validated against high-frequency eddy covariance flux tower measurements from contrasting agro-ecological zones, ensuring robustness across diverse cropping systems and climatic conditions. Surface water supply was derived from daily canal diversion records and gridded rainfall data, while groundwater abstraction was indirectly estimated through a one-dimensional water balance. The sustainability of groundwater use was assessed using a Groundwater Stress Index (GWSI) representing the ratio of abstraction to recharge. Groundwater divers installed in representative locations provided additional validation of depth and salinity dynamics enabling independent cross-checks of abstraction estimates.

Results reveal marked seasonal and spatial contrasts. Perennial canal systems generally showed sustainable use (GWSI < 90%), whereas non-perennial systems heavily reliant on groundwater during canal closures experienced severe stress (GWSI > 150%). Even in nominally perennial command areas, high cropping intensity and insufficient canal deliveries drove unsustainable abstraction rates. Mapping spatial groundwater extraction highlighted hotspots where groundwater abstraction exceeded 300 mm per season offering actionable insights for targeted management. Sub-command scale analysis across 62 canal command areas further revealed strong inequities as head-end areas with higher canal allowances showed reduced groundwater stress, underscoring spatial disparities in water access. Overall, the results demonstrate that by integrating satellite-derived ETa validated with flux tower data, canal flow records and targeted in-situ monitoring, this framework provides a scalable and transferable methodology for diagnosing groundwater stress in data-scarce irrigation systems globally. By identifying seasonal imbalances and critical hotspots, this integrated water resources modelling and management offers an actionable decision-support tool for more equitable and sustainable water management in irrigation systems facing similar pressures.

Keywords: *Water budgeting, Landsat, Evapotranspiration (ET), Eddy Covariance, Groundwater Abstraction*