High-Resolution Groundwater Drought Monitoring in the Oum Er-Rbia Basin: A 1 km Downscaling Approach with Spatio-Temporal Cross-Validation

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ABSTRACT

The Oum Er-Rbia (OER) basin, a critical agricultural heartland in Morocco, faces increasing water security challenges driven by recurrent groundwater drought. While the Global Gravity-based Groundwater Product (G3P) provides essential insights into groundwater storage (GWS) variations, its coarse native resolution limits its applicability for sub-basin management. This study addresses this limitation by developing a 1 km high-resolution GWS product through a machine learning-based statistical downscaling framework tailored to the hydro-climatic complexity of the OER region. The downscaling model integrates multi-source predictor variables spanning climate reanalysis (ERA5), satellite precipitation (CHIRPS), vegetation dynamics (MODIS NDVI), multi-scalar drought indices (SPEI at 3, 6, and 12-month accumulations), static terrain attributes from the MERIT-DEM, and anthropogenic impact proxies such as irrigation extent, urban area expansion, and nighttime light intensity, as well as soil moisture from ERA5-Land. Original and lagged anomalies were included to capture delayed groundwater responses. To ensure robust out-of-sample reliability and prevent spatio-temporal data leakage, a rigorous cross-validation scheme was implemented consisting of 100 independent folds (5 spatial blocks × 20 temporal segments). The model was calibrated over 264 months of satellite-derived data (2002–2023) and independently validated against in-situ measurements from 87 monitoring wells covering the 2010–2023 period. Results show that the 1 km downscaled product improves the detection of groundwater depletion hotspots in intensive irrigation zones such as the Tadla plain, which are typically masked at coarser resolutions. The 100-fold cross-validation indicated satisfactory predictive performance across the basin's distinct hydrogeological zones ($R > 0.60$). Feature importance analysis revealed that SPEI-12 and lagged precipitation are among the dominant drivers of GWS variability, with a characteristic groundwater response lag of approximately 3 months. These results suggest that the framework can effectively disaggregate global-scale gravity signals into locally relevant groundwater drought information. This research provides a high-resolution monitoring tool for groundwater drought in semi-arid environments. By bridging the scale gap between satellite gravity observations and local water management needs, the developed framework supports targeted drought mitigation and sustainable groundwater governance in the Oum Er-Rbia basin.

Keywords: Groundwater drought; Oum Er-Rbia; G3P downscaling; Spatio-temporal cross-validation; Machine learning; Remote sensing.