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Downscaling and Gap-Filling GRACE-Based Terrestrial Water Storage Anomalies Using Bias-Aware Machine Learning

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This study presents a methodological framework to temporally reconstruct and spatially downscale GRACE Terrestrial Water Storage (TWS) anomalies using a bias-aware Random Forest model for the transboundary Bug River Basin (Poland–Ukraine–Belarus). The approach incorporates three main innovations that enhance satellite-based TWS estimation. First, missing monthly TWS anomalies were reconstructed using an RF model driven solely by lagged GRACE values and calendar-month information, which avoided information leakage from auxiliary hydrological predictors and yielded a temporally continuous TWS record despite data gaps, including the 2017–2018 GRACE–GRACE-FO hiatus. Second, RF was used to downscale the reconstructed GRACE-derived TWS to a 0.1°×0.1° resolution, using precipitation, evapotranspiration, river runoff, and soil moisture as predictors, together with elevation, lithology, and land-cover class as static physiographic attributes. Third, a bias-aware, mass-conserving block-wise correction was applied to reconcile the downscaled fields with the original GRACE water mass at coarse resolution, by redistributing monthly systematic errors within spatial blocks using river-runoff-based weights, thereby enforcing exact mass-balance closure while preserving physically meaningful sub-grid variability.

The results indicate that GRACE-derived TWS dynamics are best captured by a predictor with an integrated origin — river runoff — rather than by individual hydrometeorological drivers, underscoring the importance of multivariate approaches to downscaling. The combined use of hydrometeorological parameters allows the model to capture complementary aspects of the storage balance that are not evident from any single predictor alone. In terms of predictive skill, the 1-month lag dominates, consistent with strong month-to-month persistence in TWS. Month (the seasonal indicator) shows moderate importance. Among the independent predictors, hydrological variables were the dominant controls on the predicted GRACE-derived TWS values, with the three-month rolling mean of river runoff being the most influential predictor. The northern regions of the Bug River Basin exhibit stronger and more regular seasonal cycles, which enhances the effectiveness of the lagged predictors and seasonal encoding used in the imputation model. By contrast, the southern areas tend to show more episodic hydrological variability, potentially driven by localized precipitation extremes, rapid runoff responses, or human water management, which reduces temporal autocorrelation and limits predictability based solely on past GRACE observations. The spatial distribution of linear trends in GRACE-derived TWS reveals a coherent pattern of long-term storage decline over the full 2002–2024 period, with pronounced spatial heterogeneity: the magnitude of decline increases toward the southern part of the study area, where the strongest negative trends are observed.

The proposed methodological framework, strengthened by rigorous spatiotemporal cross-validation

and physically based mass-conservation constraints, enables improved monitoring and forecasting of groundwater in transboundary catchments and facilitates the reconstruction of continuous TWS changes over time and space, which is particularly valuable for regions with sparse or conflict-disrupted in-situ observation networks.