Quantifying Renewable Groundwater Stress and Developing a Groundwater Quantity Stress Index for the Philippines Using Feature Importance Analysis

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ABSTRACT

Groundwater supports domestic supply, irrigation, and drought buffering in the Philippines, but national-scale assessment remains constrained by sparse observation wells, outdated baselines, and fragmented datasets. This study quantified a storage-based Renewable Groundwater Stress proxy (RGS) and developed a provincial Groundwater Stress Index (GWSI) for the Philippines. RGS was computed using Global Land Data Assimilation System 2.2 with Gravity Recovery and Climate Experiment data assimilation (GLDAS 2.2. GRACE-DA), which provides montly groundwater storage (GWS) data from February 2003 onward, and was expressed as the ratio of deseasonalized GWS trend to a renewable-input proxy based on groundwater runoff/baseflow. The GWSI was constructed from indicators representing supply (mean annual rainfall (P_{μ}), rainfall variability (P_{cv}), rainfall trend (P_{m})), demand (groundwater abstraction permits (GW_{perm}), population change (Pop_{chg}), irrigated area change(I_{chg})), and vulnerability/potential (built-up change (BU_{chg}), forest/brushland change (FB_{chg}), productive aquifer extent (Aq_{prod}), low-infiltration soil extent (S_{low}), and slope (Sl_{30})). Indicator redundancy was screened using principal component analysis. A Random Forest classifier was then used to model provincial groundwater storage trend classes, and feature importance was interpreted using Shapley Additive Explanations to derive data-driven indicator weights.

Results showed that positive GWS trends were concentrated mainly in northwestern and northern Luzon, whereas declining trends were more common in many Visayas and southern to eastern Mindanao provinces. Temporal variability analysis also showed that several provinces in western and central Luzon exhibited comparatively dynamic monthly GWS behavior, with large month-to-month changes and wide within-year amplitudes. Temporal analysis showed that GWS variability was concentrated around the late dry season to early wet season transition. The largest average month-to-month swings occurred from June to August, peaking in July, while the largest deseasonalized anomaly spread occurred from February to June, peaking in May. These periods broadly correspond to the Philippines' transition from the hot dry season into the rainy season, when rainfall onset and recharge conditions become more variable. Validation against streamflow low-flow indicators showed modest but consistent positive associations, supporting the use of GLDAS 2.2. GRACE-DA GWS as a broad regional proxy, while also confirming scale-related limitations in smaller basins. Among the GWSI indicators, P_{cv} had the highest contribution (23.38%), followed by P_{m} (11.78%) and S_{low} (10.38%), indicating that hydroclimatic variability and recharge-related landscape controls were more influential than the demand proxies included in the model. This is also consistent with the structure of the GLDAS GRACE-DA groundwater storage dataset, which is primarily influenced by climate-driven water balance processes and does not explicitly represent groundwater pumping as a direct forcing term, as noted by Li et al. (2019). Consequently, hydroclimatic controls are expected to exert a stronger influence on the modeled groundwater storage signal than administrative or indirect demand indicators. The final GWSI highlighted high-stress provinces particularly in the Cordillera and parts of Luzon, while the RGS results more strongly emphasized several coastal, island, and low-recharge settings.

Comparison of RGS and GWSI showed only partial agreement, indicating that the two frameworks capture related but different dimensions of groundwater stress. In general, provinces with high GWSI but low RGS were interpreted as areas of structural or latent vulnerability, where unfavorable hydroclimatic and physical conditions may increase stress risk even when current storage response relative to recharge remains less severe. In contrast, provinces with *high RGS but low GWSI* were interpreted as areas where storage decline relative to renewable input was already unfavorable, but where recharge uncertainty, coastal setting, or local hydrogeologic complexity may not be fully captured by the composite indicator framework. Overall, the study shows that combining a storage-response metric with a multi-indicator stress index provides a more complete national baseline for identifying groundwater-stress hotspots, interpreting dominant drivers, and prioritizing monitoring and governance reforms in the Philippines.