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Assessing Actual Groundwater Recharge under Climate Variability and Irrigation Pressure in the Upper Guadiana Basin (Central Spain)

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Climate variability and intensifying water use are increasingly altering groundwater systems in semi-arid regions, challenging sustainable water resources management at large spatial scales. The Upper Guadiana Basin (UGB), covering an area of approximately 16,000 km² in central Spain, is a representative groundwater-dependent agricultural system, where long-term irrigation-driven abstractions have caused persistent aquifer depletion. In this context, the development of coupled large-scale hydrological–hydrogeological modeling frameworks, where the main objective of the hydrological model is to calculate groundwater recharge, is essential to realistically assess groundwater dynamics under climate and water-use change.

In this study, we assessed basin-scale groundwater recharge using the mesoscale Hydrologic Model (mHM) for the period 2006–2018. The model was forced with gridded precipitation and temperature data, and calibrated by fitting river-flow at several gauging stations. Model results indicated substantially lower groundwater recharge compared to values expected from hydrogeological knowledge of the basin. This discrepancy is interpreted as evidence that, in the absence of explicit groundwater abstraction schemes, mHM implicitly compensates irrigation-induced groundwater losses by reducing simulated recharge, since this is the only way to minimize baseflow and thus fit the observed measurements during dry periods. Consequently, simulated recharge would represent an “actual groundwater recharge” that integrates both climatic controls and groundwater pumping impacts, rather than natural recharge alone.

To demonstrate that the discrepancy between natural recharge and that calculated by the model may be due to the high rates of groundwater extraction for irrigation, we analytically estimated this discrepancy by combining the irrigated areas from CORINE Land Cover (Coordination of Information on the Environment from the European Environment Agency’s Copernicus Land Monitoring Service) and SIGPAC (Sistema de Información Geográfica de Parcelas Agrícolas) datasets, with crop-specific irrigation requirements derived from FAO guidelines.

The results show that the difference between natural recharge and that calculated by the model is equal to the estimate obtained when considering crop water demand. This finding is of paramount importance for the development of large-scale regional models in arid areas where aquifers are severely overexploited and pumping rates are typically unknown, either due to the lack of meters or the presence of hundreds of unlicensed wells. In these cases, the recharge calculated with the hydrological model allows pumping effects to be incorporated indirectly, representing a major methodological advance and substantially improving model representativeness. Moreover, the results enable the characterization of the spatial distribution of pumping, facilitating the identification of the most critically overexploited areas and supporting the implementation of targeted management measures to improve water resources governance.