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"Towards multi-functional agro-ecosystems
promoting climate resilient futures"

Inferring socio-ecological influences on smallholder conjunctive irrigation patterns

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Abstract

Water scarcity is a pressing global challenge, with agriculture accounting for the largest share of freshwater use and contributing significantly to water stress. In developing countries such as Pakistan, this issue is particularly acute, where unreliable surface water supplies necessitate widespread groundwater extraction to meet crop water demand in the wake of climate variability and drought risks. Direct measurement of farmer-level conjunctive groundwater use remains infeasible due to the absence of metering infrastructure, heterogeneous pumping technologies, and limited observational data. This study addresses this gap by focusing on a smallholder irrigation watercourse in Central Punjab, Pakistan, where farmers operate under a shared surface-water allocation system while simultaneously drawing from a common groundwater aquifer to meet crop water demand. We integrate data from an indigenously developed soil moisture sensor network (WITSMS), rainfall records, farm boundaries, and irrigation rosters to develop a data-driven framework for inferring farmer-level groundwater reliance without direct measurements. By combining field-scale soil moisture dynamics with a seasonal soil-water balance model, we reconstruct the relative contributions of surface water, rainfall, and groundwater. This hydrological accounting, complemented by groundwater level observations, enables the analysis of farmer interactions and pro-ecological behaviours within a coupled socio-ecological system (SES). More specifically, we employ a parametric socio-ecological model to infer farmer-level water-use decision responses and examine how these responses are associated with emergent groundwater extraction patterns and potential long-term resource stress. The study offers both a scalable methodology for estimating groundwater use under data-scarce conditions and an SES perspective for understanding how water stress propagates within shared irrigation systems, with implications for groundwater governance in smallholder contexts, leading to effective advisory systems, equitable water allocation, groundwater regulation, and the promotion of participatory governance. Moreover, water conservation and other climate-resilient practices discourage intensification, promotion of biodiversity, and the emergence of truly multi-function agro-ecosystems.

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