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Hysteresis, regime shifts, and non-stationarity in aquifer recharge-storage-discharge systems

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Based on physical principles and geological information we develop a parsimonious aquifer model for Silver Springs, one of the largest karst springs in Florida. The model structure is linear and time-invariant with recharge, aquifer head (storage) and spring discharge as dynamic variables at the springshed (landscape) scale. Aquifer recharge is the hydrological driver with trends over a range of time scales from seasonal to multi-decadal. The freshwater-saltwater interaction is considered as a dynamic storage mechanism. Model results and observed time series show that aquifer storage causes significant rate-dependent hysteretic behavior between aquifer recharge and discharge. This leads to variable discharge per unit recharge over time scales up to decades, which may be interpreted as a gradual and cyclic regime shift in the aquifer drainage behavior. Based on field observations, we further amend the aquifer model by assuming vegetation growth in the spring run to be inversely proportional to stream velocity and to hinder stream flow. This simple modification introduces non-linearity into the dynamic system, for which we investigate the occurrence of rate-independent hysteresis and of different possible steady states with respective regime shifts between them. Results may contribute towards explaining observed non-stationary behavior potentially due to hydrological regime shifts (e.g., triggered by gradual, long-term changes in recharge or single extreme events) or long-term hysteresis (e.g., caused by aquifer storage). This improved understanding of the springshed hydrologic response dynamics is fundamental for managing the ecological, economic and social aspects at the landscape scale.