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The impact of aeration zone flow dynamics for critical zone compartmentalization and functioning in hillslope terrain

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In the aeration zone, transients of water-saturation, fluid flow, (re-)distribution and cycling of matter and energy may strongly control the compartmentalization of subsurface ecosystems. Especially, seasonal or episodic dynamics of flow and flow paths within the aeration zone, cause transient groundwater flow partitioning that guides the quality evolution and ecology of groundwater resources. However, flow dynamics and matter cycling within the aeration zone are typically less explored and considered in resource modeling and management. This is particularly the case for topographic recharge areas with large aeration zones, themselves lacking productive groundwater bodies, but most important for the quality of the seepage. In the Hainich Critical Zone Exploratory (central Germany), we investigate the interplay of aeration zone dynamics for groundwater quality evolution along a hillslope monitoring transect. In the widely-distributed setting of alternating mixed carbonate-/siliciclastic bedrock, lysimeters, aeration zone collectors and multi-level monitoring wells were installed to access the subsurface compartments down to ∼90 m. From up to eight years of monitoring weather, ground temperatures, multi-depth hydraulic heads and non-conservative environmental tracers, we were able to reconstruct hidden phenomena like localized recharge and fluctuating perched groundwater that also cause flow transients in the phreatic zone. Likely shaping the subsurface ecosystems, we found aeration zone-loading of waters, that bypass the argillaceous, oxygen-deficient overburden and cause, for instance, oxygenation of the main aquifer by seasonally ascending flow. Furthermore, our data highlight the role of (multiple) snowmelts that strongly contribute to the groundwater budget in our hillslope terrain with temperate climate.