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Experimental Assessment of Potential Water Quality Changes Induced by Groundwater-Level Fluctuations at a Groundwater Dam Site

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Groundwater dams are recognized as a promising strategy for securing water resources during drought periods intensified by climate change. For sustainable operation, evaluation of potential groundwater quality deterioration during storage is essential. Groundwater-level fluctuations associated with recharge and abstraction can modify water content, dissolved oxygen (DO), pH, and redox conditions within the variably saturated zone, potentially triggering biogeochemical reactions that influence groundwater quality. To assess these effects, laboratory column experiments were conducted using soils collected from different sites. Pore water samples were obtained at multiple depths to examine hydrochemical variations under simulated groundwater-level fluctuation conditions. Major ion concentrations varied with soil depth, primarily reflecting groundwater advection as water-level moved upward toward saturation. The results indicate that sufficient time is required to achieve hydrochemical equilibrium along the column profile. Distinct patterns of pore water quality evolution were observed depending on soil biogeochemical characteristics. In one column, DO remained consistently low during repeated fluctuation cycles, accompanied by a substantial decrease in oxidation–reduction potential (ORP). Under these reducing conditions, active denitrification occurred together with reductive dissolution of Fe and Mn oxides. The release of Fe and Mn was followed by mobilization of trace metals, including As and Zn. Increasing the number of fluctuation cycles further enhanced the release of Fe, Mn, and associated trace metals. In contrast, the other soil columns exhibited relatively minor geochemical transformations. The distinct behavior is attributed to high initial organic matter content in the soil, which generated elevated dissolved organic carbon (DOC) serving as electron donors for microbial processes. Consequently, redox reactions consuming electron acceptors such as NO3-, Fe(III), and Mn(IV) were intensified, promoting denitrification and reductive dissolution. Overall, groundwater-level fluctuation cycles play a critical role in controlling redox dynamics and water quality evolution in the variably saturated zone. Spatial heterogeneity in soil geochemical properties must therefore be carefully evaluated to minimize the groundwater vulnerability to the contamination by indigenous factors and to identify suitable sites for sustainable groundwater dam development.