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Tracing Contact Water Migration in Groundwater Systems: A Multi-Source Isotopic Mixing Model Approach

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Characterizing the interaction between mine-contact waters from Waste Rock Dumps (WRD) and Tailings Storage Facilities (TSF) and natural aquifers is essential for assessing impacts on groundwater quality and the hydrogeochemical integrity of high-altitude environments. In the Central Andes (>3,000 m a.s.l.), under hyper-arid Atacama Desert–type conditions, this task is complicated by fracture-dominated flow, low natural recharge, and overlapping hydrochemical signatures. However, these settings are particularly favorable for the use of stable isotopes ($d^{18}O$ and $d^{2}H$) as conservative tracers, as process waters experience strong kinetic fractionation and follow evaporation trends that diverge from the Local Meteoric Water Line (LMWL), generating distinct isotopic fingerprints relative to pristine groundwater.

An isotopic–hydrochemical framework is presented to quantify mixing between mine-contact waters and regional aquifers in such environments. Long-term monitoring data from downstream wells are interpreted using conservative and reactive multi-component mixing models implemented in PHREEQC and custom Python scripts. Water from the TSF pond is treated as a proxy for contacted seepage and mixed with two hydrochemical types of natural groundwater. $d^{18}O$, $d^{2}H$ and Cl are used as principal tracers, enforcing internally consistent mixing proportions across species within an uncertainty of approximately ±10–15%. A three-end-member mixing triangle in isotopic space is used to derive volumetric contributions of TSF-derived water for each monitoring point and sampling date.

Model results are validated against major-ion chemistry and NO_3/Cl molar ratios, which provide an independent qualitative check on the presence of dilute shallow waters versus low NO_3 contact waters. The combined criteria allow the definition of isotopic domains potentially affected by TSF seepage, including zones where the inferred proportion of contact water remains low (typically < 20%) but non-negligible. This approach delivers a transferable methodology for resolving seepage pathways and quantifying uncertainty in data-scarce settings. When supported by a robust monitoring network, the framework functions as a predictive tool for defining long-term chemical thresholds and guiding proactive environmental management in porphyry copper operations under hyper-arid conditions.