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Cold-temperature performance of ZVI-based permeable reactive barriers for multi-contaminant (NO_3^-, As, U) removal

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Increase in mining activities in the sub-arctic regions raises major challenges for environmental management that are amplified by the harsh climatic conditions that suppress kinetic reactions underpinning treatment. In the North, the remoteness limits access to infrastructure and materials as well as human labour. Thus, the utilization of (semi-)passive water treatment systems is encouraged. Among them, permeable reactive barriers (PRB) have been identified as cost-effective and low-maintenance systems allowing the treatment of mine-impacted water. We evaluate the performance and mechanisms of bench-scale columns PRBs designed for simultaneous removal of nitrate, arsenic, and uranium at 5 °C using bench-scale flow-through columns (36 weeks) containing varying proportions of zero-valent iron (ZVI), gravel, and wood chips. To probe abiotic–biotic coupling under cold conditions, columns were amended with sodium acetate during weeks 20–33 to stimulate denitrification. Solid- and aqueous-phase speciation was constrained by X-ray Absorption Spectroscopy and PHREEQC modeling.

Across all ZVI-bearing media, arsenic removal persistently exceeded 95% and was governed by adsorption/coprecipitation with Fe(oxyhydr)oxides formed during ZVI corrosion—demonstrating robust As attenuation even at 5°C. Nitrate showed limited removal in the absence of acetate, but improved to ~50% during amendment, indicating partial, kinetically constrained denitrification to N2 under cold temperatures. Uranium was >95% removed prior to amendment, predominantly by U(VI) adsorption to Fe(oxyhydr)oxides; however, remobilization occurred during acetate dosing, consistent with enhanced Ca–carbonate complexation that weakened U sorption and promoted desorption.

These experiments show that PRB technology holds promise for multi-contaminant removal under cold conditions, while exposing ongoing challenges associated with concurrent removal of contaminants exhibiting contrasting geochemical behavior.