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Advective Colloidal POM Input Drives Transient Anoxia and Redox Cycling in Columbia River Hyporheic Zone Sediments

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Large stage fluctuations in the Hanford 300 Area of the Columbia River (WA), driven by seasonal discharge and hydroelectric dam operations, create conditions conducive to advective influx of fine-grained colloidal particulate organic matter (POM) into near-surface hyporheic sediments — a process with important but poorly constrained implications for redox heterogeneity and elemental cycling.

Novel POM trap deployments (Feb–Mar and Jun–Jul 2020) showed that particulate organic carbon accumulates from background levels of ~0.06% to ~0.3% dry weight in the upper 10 cm of the riverbed. Column transport experiments with fresh periphyton biomass constrained a reversible sorption/irreversible filtration model for colloidal POM transport. In situ optical DO probes at 20 cm depth recorded sustained near-anoxic conditions and large periodic DO fluctuations — unexpected given high hydrologic exchange flow (HEF) rates and oxygen-rich source waters. K-means clustering of co-deployed conductivity and water level data confirmed tight coupling between DO variability and hydrologically-driven shifts in flow direction and magnitude.

A one-dimensional advection-dispersion-reaction model, incorporating POM transport, first-order POM hydrolysis to dissolved organic matter (DOM), and a comprehensive sequential redox reaction framework (Modified Monod primary redox kinetics; second-order reoxidation of reduced inorganic species), was forced with measured hourly stage data from 2020. Simulations show that DOM metabolism alone cannot produce observed anoxia. In contrast, advective colloidal POM input generates transient anoxia in the upper 20–30 cm, with DO depletion lagging peak POM accumulation by ~one month, triggering anaerobic metabolic pathways and nitrogen redox cycling during periods of maximal organic matter processing. On shorter timescales, flow reversals produce DO spikes consistent with in situ observations, reflecting the dynamic balance between oxygen consumption and advective resupply.

These results identify fresh mobile colloids as an underappreciated driver of redox hotspots in hyporheic sediments, with broad implications for nutrient and contaminant mobility, greenhouse gas production, and carbon processing in large regulated river systems.