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Stable Isotopes as a Decision-Support Tool for Managing Legacy Groundwater Contamination

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Compound-Specific Isotope Analysis (CSIA) provides direct evidence of the transformation of a wide range of groundwater contaminants, representing a versatile and robust tool for evaluating the effectiveness of sustainable and cost-effective in situ remediation strategies, i.e., engineered and natural attenuation. Despite being a well-established proxy for bioremediation monitoring, particularly for chlorinated solvents, CSIA is not yet routinely integrated into standard site management protocols in Europe due to limited familiarity among practitioners and the perceived complexity of isotope data interpretation.

This contribution discusses: (i) the practical benefits of integrating multi-isotopic tools ($\delta^{13}C$- and $\delta^{37}Cl$-CSIA) with site conceptual models, hydrogeochemical and microbiological indicators to support evidence-based decisions in remediation projects; and (ii) an application-oriented framework to bridge academic and industrial practice for the use of CSIA in groundwater remediation.

A case of extensive operational-scale application of CSIA is presented. Isotopic, hydrochemical, and biomolecular data were systematically collected at a chlorinated hydrocarbon–contaminated aquifer beneath a large former industrial site to assess the performance of Enhanced Natural Attenuation. Monitoring was conducted across different areas of the site under varying baseline conditions and biostimulation amendments, covering all stages from pilot testing to post-operation monitoring. Isotopic results provided evidence of in situ reductive dechlorination and contaminant rebound, consistent with observed contaminant concentration trends, favorable redox conditions, and increased abundance of organohalide-respiring bacteria and reductive dehalogenase genes.

Overall, the study highlights the value of integrated monitoring programs and the importance of structured guidelines, and stronger regulatory recognition to facilitate the transition of CSIA from research to an operational decision-support tool for managing legacy groundwater contamination.