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Editorial: Advances and emerging methods in tracer hydrogeology

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Editorial on the Research Topic
Advances and emerging methods in tracer hydrogeology

Groundwater, although generally hidden to our eyes, is not only an important component of the hydrological cycle, it's also of vital importance for society. Indeed, groundwater represents our largest readily available source of clean drinking water. To this day, however, the elusive nature of groundwater prevents us from directly measuring most of its renewal processes, its passage through the subsurface and its discharge into surface water bodies. At the same time, an increased dependence of society on groundwater, and increased threats to its quality, are heightening the need for innovative techniques to characterize and protect groundwater resources.

Hydrological tracers are a critical tool in helping our society to better understand and manage this precious and vital resource, as hydrological tracers allow us to evaluate groundwater residence times, mixing ratios between groundwater of different origins, as well as numerous other hydrologically relevant parameters. While observations of groundwater levels and streamflow discharge may be limited in providing insights into subsurface processes and exchange fluxes between surface and subsurface water bodies, their integration with hydrological tracer observations opens up important perspectives for monitoring and managing our water resources (Abbott et al., 2016; Schilling et al., 2019). An ideal hydrological tracer is either conservative or representative of the process we are interested in, readily measurable, and able to inform critical variables and parameters of the models that we use to manage our water resources. Environmental gas tracers such as dissolved noble gases, for example, function as near-ideal tracers of groundwater residence times, mixing and flow paths (Suckow and Gerber, 2022); however, challenges related to the efficient and accurate measurement of environmental gas tracers and the incorporation of these data into quantitative models have held back their usage. Additionally, there has been little research on the evaluation of the information content (or data worth) of more recently emerging tracers, limiting our understanding of their true potential. This clear need for methodological development has recently led to significant efforts to improve both sampling and measurement methods, and to develop more robust and computationally efficient data assimilation techniques.

Owing to recent advances in both analytical and numerical techniques and methods, the information that we are now able to gain from hydrological tracers—both artificial and natural—has become much more interdisciplinary, precise, and spatially and temporally resolved (Tetzlaff et al., 2015; Brunner et al., 2017; Benischke, 2021; Schilling et al., 2023). The articles in this Research Topic eloquently illustrate the capacity of emerging gas tracer techniques to provide valuable quantitative knowledge about hydrological processes, including the connectivity of surface and subsurface water resources. While there is too often a disconnect between groundwater and surface water research, these advances provide new tools for evaluating the dynamics of water resources in a comprehensive and interdisciplinary way.

In "*New experimental tools to use noble gases as artificial tracers for groundwater flow*," Brennwald et al. combine a recently developed gas-equilibrium membrane-inlet mass spectrometer (GE-MIMS) with a gas diffuser to artificially inject gas tracers as Dirac-like pulses into groundwater. Noble gas transport is compared against injected fluorescent dye tracers, and the study demonstrates the potential of using noble gases as novel artificial tracers for groundwater and groundwater-surface water interactions.

The article "*New experimental approaches enabling the continuous monitoring of gas species in hydrothermal fluids*" by Giroud et al. presents two new experimental methods that allow water vapor condensation, which impedes measuring environmental gas tracers in hot thermal fluids (i.e., in natural waters with temperatures around 65°C or more), to be avoided during sampling. Both methods were deployed on two different deep thermal waters in Lavey-les-Bains (Switzerland) and Beppu (Japan). Coupled to the GE-MIMS portable mass spectrometer, the proposed methods were able to provide a consistent and adequate solution to continuously measure gas species in thermal waters.

In the article "*Explicit simulation of environmental gas tracers with integrated surface and subsurface hydrological models*," Delottier et al. proposed a mathematical formulation to account for gas/water partitioning during the production of environmental gas tracers emanated in the subsurface. The formulation is implemented in a single-phase integrated surface-subsurface hydrological model (ISSHM) and verified against outputs from a multiphase fluid flow modeling software. The developed method is crucial for improving the capacity of single-phase ISSHM to simulate gas tracer concentrations in complex environments such as alluvial river-aquifer systems.

In "*A lumped parameter model to evaluate the relevance of excess air as a tracer of exchanged flows between transmissive and capacitive compartments of karst systems*," Sivelle et al. combined excess air (EA) and spring discharge observations to improve the understanding of recharge processes and the connectivity of different compartments in karst systems. Both types of observations could be jointly reproduced with a lumped parameter model of a multi-compartment karst system under the assumption of a linear relationship between water level variations and EA formation, thereby supporting existing conceptual models to explain EA formation in karst systems. The study demonstrates that the use of EA measurements in karst systems can be used to reduce uncertainties of relevant parameters for the simulation of karst spring discharge.

As the papers in this Research Topic aptly demonstrate, emerging tracer techniques such as the continuous measurement of dissolved noble gases open up important new perspectives for hydrological process understanding and water resources management. Because acquisition of hydrological tracers supports the decision-making process, we are convinced that these new techniques will help in making the exploitation of our precious groundwater resources more sustainable and adaptable to future anthropogenic and climatic perturbations.

Author contributions

OS, LH, and HD wrote the editorial collaboratively. All authors reviewed and edited the manuscript. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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