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title: **Integration of environmental tracer information into groundwater modelling**

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Numerical groundwater models, which are calibrated with the help of head data are often non-unique to some degree. A fit to head data alone is necessary but not sufficient. The basic dilemma in flow modelling consists of the fact that hydraulic conductivity is in general poorly known. Since boundary fluxes, recharge rates, and fluxes to or from rivers cannot be measured directly, they have usually to be estimated independently. Both types of information are uncertain, and therefore, the resulting flow model is error-prone. Consequently, the resulting flow field is often too inaccurate for solute transport modelling. An example is the inaccurate simulation of a pollutant plume in groundwater due to uncertain boundary fluxes. Environmental tracers can offer a possibility in this case by estimating or at least by improving the boundary fluxes. Can environmental tracers help in improving flow and solute transport models in general? They can be useful at least to some degree. Environmental tracers can for example indicate that there is recent recharge, or they allow estimating the age of groundwater or its residence times, or they can yield streamline information, or ratios of fluxes including recharge rates, or effective porosity values. Indeed, many examples from the literature show that various environmental tracers were successfully used in the past to check or to improve flow models, to select among several scenarios or conceptual models, and to determine solute transport parameters. Parameter estimation using environmental tracers has usually been performed manually.

However, there exist a series of limitations for the use of environmental tracers in groundwater modelling. For example the input function is not always well known, or the age window of a particular tracer is limited. Environmental tracer data do not provide direct information on Darcy fluxes. Dissolved gas tracers yield information which is different from that of solute markers of the water molecule. Estimated porosity values can still exhibit quite some uncertainty. Moreover, the effective porosity may not be constant due to dual porosity effects. Furthermore we have to keep in mind that hydraulic heads show a momentary situation while tracer data integrate over longer time periods. The residence time of tracers in the unsaturated zone can sometimes be larger or much larger than in the saturated zone of the aquifer. This can increase the uncertainty since information on unsaturated flow conditions is usually very sparse. Nevertheless, the range of possible results from a calibrated flow model can sometimes be restricted considerably by using environmental tracer information in the modelling. This depends on the sensitivity of a particular parameter like effective porosity to simulated environmental tracer concentrations. There exist examples where transmissivity is not or only little sensitive.

We might pose the question why environmental tracers are not used more intensively in flow and transport modelling. Besides the above mentioned problems, reasons might be the relatively high costs, and the lack of knowledge about the sensitivity of a particular tracer. Moreover, too high expectations in the past may have led to frustration.

As a conclusion, environmental tracer data allow to check and to improve groundwater flow and transport models. Moreover, environmental tracers are the only available means to estimate effective porosity and travel times on the field scale. The combination of several environmental tracers with differing properties (like gaseous tracers with different diffusion coefficient and water bound tracers) is certainly more demanding, but can make the application much more reliable. The flow and transport models should be used to check the consistency of all collected data (even with respect to proxi-data, which do not enter the model directly) and to

confirm or to exclude hypotheses. As a general suggestion environmental tracer information should primarily be used for getting ideas about the conceptual model, and not necessarily for getting higher accuracy. Of course if the latter can be achieved, so much the better. The integration of environmental tracers in groundwater models can reduce the range of possible alternative interpretations, which are consistent with all observations.

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