Hydraulic characterisation of managed aquifer recharge sites by tracer techniques

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Summary: Managed aquifer recharge (MAR) is a widely accepted method for augmenting water supplies for potable and non-potable use. The success of the MAR system is often defined by a substantial removal of chemical and biological contaminants during subsurface passage. To determine removal rates and to differentiate between removal and overall attenuation due to dilution, estimation of mixing proportions is a key element of tracer applications. This report provides an overview of tracers suitable for MAR and discusses advantages and disadvantages for each tracer. The ideal tracer may be defined by: a natural or anthropogenic origin, a clear uneven distribution in the studied system (e.g. sharp contrast between source and native groundwater), non-toxicity (human and environmental), easy and cost-effective measurement, and a conservative (neither sorbed nor (bio-)chemical reactive) or at least predictable chemical or physical behavior. A huge number of tracers exist, each with advantages and disadvantage. Tracers can be dissolved (e.g. chloride, bromide), stable or radioactive isotopes (e.g. ^{18}O, ^{3}H), gaseous (e.g. SF_6) or a physical properties (e.g. temperature). The use of heat as a tracer has several advantages over hydrochemical tracers. Temperature is inexpensive, easy and a robust parameter to measure. In contrast to chemical tracers, no laboratory analysis is required and the data is available immediately. Finally, a multi tracer approach ($\geq$ 2 tracers) is always recommended, because the ideal tracer is rarely found. A reasonable combination is at least one conservative tracer (e.g. stable isotopes of water) with a retarded tracer (e.g. temperature) to evaluate short travel times from the point of recharge (e.g. riverbed or pond) to the recovery well.

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Preface

This report is part of the task 11.1 as shown in the DoW of the DEMEAU project. An example of field scale tracer application carried out within the DEMEAU project is found in deliverable 11.2.

1   Introduction

Managed aquifer recharge (MAR) is a widely accepted method for augmenting water supplies for potable and non-potable use. The success of a MAR system is often defined by a substantial removal of chemical and biological contaminants during subsurface passage. Some of the removal processes are time dependent (e.g. biodegradation, inactivation or die-off), and the understanding of travel times from the source (e.g. pond, river, lake) to the point of abstraction is a key element in the management of aquifer recharge. In virtually all MAR cases the abstracted water is a mixture between the native ambient groundwater and the recharged source water. The observed overall attenuation of contaminants is usually achieved by removal processes and dilution effects (Grützmacher et al., 2011). Therefore, information about flow velocities, travel times, fluxes between surface- and groundwater as well as mixing proportions can be obtained by different hydrogeological tracer parameters. The ideal tracer is defined by the following characteristics:

- a natural or anthropogenic origin
- a clear uneven distribution in the studied system (e.g. sharp contrast between source water and native groundwater)
- non-toxicity (human and environmental)
- easy and cost-effective measurement
- conservative (neither sorbed nor (bio-)chemical reactive) or at least predictable chemical or physical behavior

A huge number of tracers exist, each with advantages and disadvantages. Tracers can be dissolved (e.g. chloride, bromide), stable or radioactive isotopes (e.g. ^{18}O, ^{3}H), gaseous (e.g. SF_6) or a physical property (e.g. temperature, electrical conductivity). A tracer can be intrinsically occurring or is added to the system over a short period of time (deliberate tracer). Intrinsic tracers can be of natural or anthropogenic origin and many of the tracers used in MAR systems are intrinsic tracers. Deliberate tracers are artificially introduced only for the purpose of the test itself. Deliberate tracer tests require a sound understanding of the hydrogeology, a detailed planning and, depending on the purpose, are often time consuming. This report discusses the use of tracers during MAR systems for hydraulic characterization. Tracers which can be used for direct hydrochemical evaluation (e.g. $\delta^{15}N$ and $\delta^{18}O$ in nitrate) are not in the scope of this report. More information on this topic can be found in IAEA (2013).

2   Background

In MAR systems tracers are required to work with short residence times, usually in the range of few days to few weeks. Different input concentrations of tracers and corresponding concentrations measured in abstracted and native groundwater are shown schematically in Figure 1.
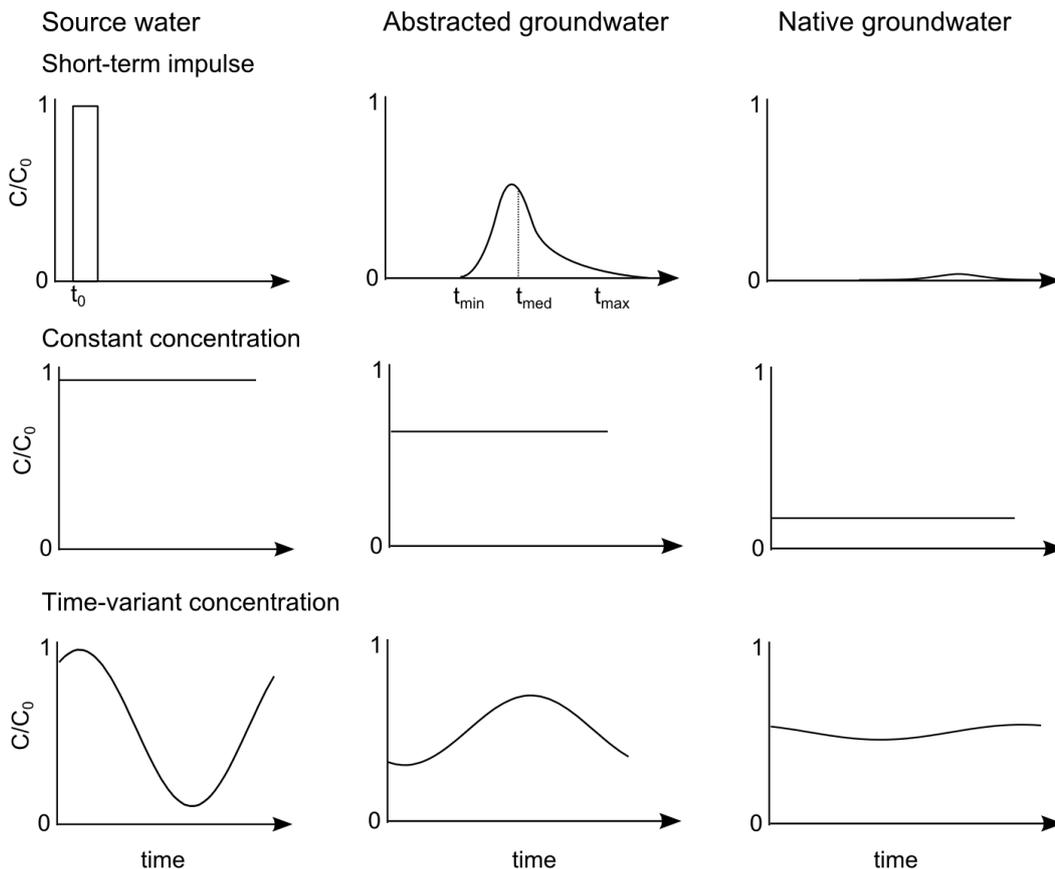
Figure 1:   Different tracer input concentrations in the source water and corresponding concentrations measured in abstracted and native groundwater during MAR.

Deliberate tracer tests are usually designed as short-term impulse tests (Dirac impulse), but also intrinsic tracers (or tracer similar) may show a sharp defined input signal. The ideal tracer for short-term impulse is not detectable in the native groundwater prior to testing. The tracer is transported by advection and dispersion and the breakthrough is recorded in the abstraction well. Tailing effects are often observed and can be a result of retardation of a small fraction of the tracer. Retardation can be caused by dual porosity, influence of prolonged flow paths, hydro mechanical dispersion or chemical retardation. Tracer breakthrough during MAR is discussed by the following two essential statistical parameters:

- First occurrence of tracer (C_{min}): The first occurrence depends on the detection limit of the applied tracer. The first occurrence of the tracer (t_{min}) is the critical arrival time for MAR systems, as it

describes the shortest flow path. During risk assessment t_{min} is used for a conservative travel time approximation. The maximal effective flow velocity (V_{max}) is calculated with the known flow distance (x) according to: $$V_{max} = \frac{x}{t_{min}}$$

- Median concentration (C_{med}): the median travel time is calculated when 50% of the tracer mass (t_{med}) is detected in the abstracted well. The median velocity is often described as the "true" travel time and can be calculated by $$V_{med} = \frac{x}{t_{med}}$$

Time-variant concentrations are found by intrinsic tracers which can be used for assessing travel times. The input curve, idealized as a sine curve in Figure 1, is found in attenuated concentration (i.e. reduced amplitude) and shifted in time.

A relative constant concentration in the input with a pronounced contrast to ambient groundwater can be used to calculate mixing proportions based on a conservative two-member mixing model according to:

$$X = \frac{C_{recovery} - C_{native}}{C_{source} - C_{native}} \times 100\% \qquad \textbf{eq. 1}$$

where:

X = percentage of recharged source water in the well

C = concentration of tracer in native, recovery and source water

The accuracy of the calculated percentage X depends on the appropriate identification of the end-member concentration (Carrera et al., 2004). This can be challenging because in many cases spatial and temporal variability renders end-members to become noisy (Carrera et al., 2004). A simple statistical procedure to check the contrast between the source water and native groundwater is described by Stuyfzand (2010). With this procedure it is possible to identify the most suitable tracer(s) for the regarded MAR system irrespective of the hydrogeochemical zone.

3 Types of tracers for MAR

3.1 Dissolved (e.g. Br, Cl, electrical conductivity)

Dissolved tracers (e.g. Br, Cl) or sum parameters of dissolved compounds (e.g. electrical conductivity) are standard parameters with low analytical costs. Some applications of dissolved tracers during MAR are summarized in the following.

Wett et al. (2002) calculated mixing proportions based on eq.1 at an induced bank filtration (IBF) site at the Enns River (Austria) by using electrical conductivity (EC) as a tracer. The authors assumed EC in native groundwater to be constant and used calculated mixing proportions to calibrate a numerical model. EC was considered as a conservative tracer, which neglects the commonly observed increase of EC during bank filtration due to dissolution processes. A similar approach was followed by Sheets et al. (2002) using EC and temperature to evaluate travel times at a riverbank filtration site in Cincinatti, Ohio (USA). The authors concluded that EC, which was measured at different depths and locations can be used to estimate travel times during IBF.

Stuyfzand (2010) reported about 28 environmental tracers which were used at MAR sites in a coastal aquifer in western Netherlands for evaluating mixing proportions between source water and native groundwater. Based on statistical ranking the author found that Cl/Br-ratio in combination with stable ^{18}O isotope of the water were suitable for a wide range of geochemical conditions. Second best tracers are non-conservative, reactive tracers with a retardation factor of one (e.g. EC, HCO_3 or SO_4) that may perform well if the reaction pronounces the contrast between end-members. Reactive tracers including temperature, F, I, Mo, B, Li, Sr, Na, K, and Mg were classified as not, or only under certain circumstances, useful. B and Mo for example are useful proxies for mixing proportions in the shallow dune aquifer, but experience sorption or desorption in deeper sections of the aquifer. A fourth group of tracers including T/^{3}He, anthropogenic Gd, pharmaceutically active compounds (PhACs), or pesticides are either difficult to sample (e.g. ^{3}He) or relative costly to analyse and therefore not considered as an ideal tracer (Stuyfzand, 2010).

Bekele et al. (2013) measured Br in the unsaturated zone at a soil aquifer treatment (SAT) site through suction cups. The source water (secondary treated effluent) was spiked by NaBr and KBr. The deliberate tracer test yielded travel times in the range of few days before reaching the water table.

Sewage derived compounds (Cl, B, SO_4) were used by Massmann et al. (2007) at bank filtration sites in Berlin (Germany) to evaluate mixing proportions and travel times. Monthly measurements in surface water showed fluctuations of Cl and B which are, in contrast to stable isotopes of water, not seasonally but rather influenced by upstream activities. Anyhow, the authors found that travel time analysis of sewage derived tracers (B, Cl) are confirmed by isotope results, but due to their pronounced seasonality isotopes of water are better suited. Most important findings of dissolved tracers during managed aquifer recharge are summarized in Table 1.

Table 1:   Dissolved tracers during managed aquifer recharge.

Tracer	Site and test description	Source water	Summary	References
Br	Atlantis gallery (Australia), SAT, deliberate tracer test	Treated effluent	Used to evaluate travel time (~ 4 days) in unsaturated zone	Bekele et al. (2013)
Cl, Br	Dune infiltration, intrinsic test	River water	conservative, best suited for wide range of hydrogeochemical settings	Stuyfzand (2010)
EC, HCO3, SO4			Potentially reactive but not retarded, useable with great care	
F, I, Mo, B, Li, Sr, Na, K, Mg			Potentially reactive, not recommended or only useable with great care	
EC	IBF Enns River (Austria), intrinsic test	River water	Mixing proportions used to calibrate numerical model	Wett et al. (2002)
EC, temperature	IBF, Cincinatti, Ohio (USA), intrinsic test	River water	Travel time evaluation	Sheets et al. (2002)
B, Cl	Two IBF sites, Berlin (Germany), intrinsic test	River water with treated effluent	Travel time evaluation with sewage derived tracers	Massmann et al. (2007)

EC = electrical conductivity; IBF = induced bank filtration;

3.2   Stable isotopes (e.g. δ^{18}O, δ^{2}H, ^{87}Sr, δ^{11}B, δ^{7}Li)

Stable isotopes of water (δ^{18}O, δ^{2}H) are conservative tracers with relative low analytical costs (20-50 € per sample) and widespread applications in hydrogeological studies. Stable isotopes are often used as environmental tracers due to the pronounced seasonal variation of the isotope signature in surface water

bodies. Temperature dependent fractionation processes in clouds and precipitation lead to seasonal fluctuations of isotope signatures in the surface water, which is usually depleted in [18]O and ^{2}H in winter and enriched in [18]O and ^{2}H in summer (Clark and Fritz, 1997). These seasonal fluctuations are then traced backed in the groundwater in MAR systems which rely on surface water as source water. A good overview of isotope applications for hydraulic and hydrochemical characterization during MAR can be found in IAEA (2013).

At induced bank filtration sites in Berlin (Germany) Massmann et al. (2007) were able to evaluate short travel times (1-4 months) by comparing seasonal variations of $\delta^{18}O$ and δ^2H in the surface water with attenuated and time shifted variations in the shallow groundwater. At bank filtration sites close to Prague (Czech Republic) Buzek et al. (2003) used the stable isotope [18]O to evaluate mixing proportions in the bank filtration wells. In the Turku region (Finland) a simple two end-member mixing model with stable isotopes (native groundwater with little variation and river water with seasonal fluctuations of up to 3‰ in $\delta^{18}O$ values) was sufficient (IAEA (2013) and references therein). During an aquifer storage and recovery (ASR) pilot trial in Damascus (Syria) the authors concluded that isotopes can be used to monitor recovery efficiencies during ASR by ^{18}O, but a multi-tracer approach is recommended because some tracers may not allow discrimination of native groundwater from the injected source water (IAEA (2013) and references therein).

Kloppmann et al. (2009) evaluated sewage derived tracers during dug well recharge at the Shafdan water reclamation plant (Israel). The authors used intrinsically occurring tracers (Br, $\delta^{11}Br$, δ^7Li) and measured the breakthrough in the unsaturated zone and in groundwater monitoring wells at certain distances from the dug well.

Table 2: **Isotope tracers during managed aquifer recharge.**

Tracer	Site and test description	Source water	Observed behavior	References
δ^7Li	Shafdan (Israel) Intrinsic test, pilot of dug well recharge	Treated effluent	Non-conservative, non-predictable, strongly modified during transport	Kloppmann et al. (2009)
$\delta^{11}B$			Near conservative, reversible sorption identified	
$\delta^{18}O$	Close to Prague (Czech Republic), IBF, intrinsic test	River water	Large differences in native groundwater and surface water, mixing proportions evaluation	Buzek et al. (2003)
$\delta^{18}O$	Damascus (Syria), ASR pilot	Groundwater (Spring water)	Large differences in native groundwater and surface water, mixing proportions evaluation	IAEA (2013) and references therein

$\delta^{18}O$, δ^2H	IBF sites in Berlin (Germany), intrinsic tracer test	River water with treated effluent	Seasonal fluctuations in surface water body (Δ1.8 ‰), travel time (1-4 months) evaluation	Massmann et al. (2007)
$\delta^{11}B$	Cap Bon (Tunisia), SAT	Treated effluent	Combination of $\delta^{11}B$ with B and carbamazepine used to assess mixing proportion and the effects of abstraction, natural groundwater recharge, seawater intrusion on local groundwater dynamics	Cary et al. (2013)
$\delta^{18}O$, δ^2H	Dune infiltration (Netherlands)	River water	Conservative, good performance under wide range of hydrogeochemical settings, used to calculate mixing proportions	Stuyfzand (2010)

SAT = soil aquifer treatment; ASR = aquifer storage and recovery; IBF = induced bank filtration

3.3 Heat (temperature)

Since many decades hydrogeologists investigated temperature (heat) transport in the subsurface to estimate groundwater velocities or exchange rates with surface water (Anderson, 2005; Rau et al., 2014; Stallmann, 1963; Stonestrom and Constantz, 2003). Heat is transported not only by the flowing water (advective heat flow) but also by heat conduction through solids and fluids (conductive heat flow). The mutual heat exchange of the groundwater with the surrounding aquifer material retains the heat signal compared to advective/dispersive transport, resulting in attenuation and retardation of the temperature signal.

Vandenbohede and Van Houtte (2012) investigated at a dune infiltration site in St-André (Belgium) seasonal temperature variations in the source water to evaluate travel times in the subsurface. The authors also calculated differences in infiltration rates due to changes in water viscosity. It was found that temperature provides only rough proxy and that high flow velocities during infiltration make temperature signal feasible only in the direct vicinity of the pond. The temperature signal was found to decrease quickly below measurements errors. However, compared to conservative transport, thermal transport is retarded by a factor between 1.5 to 2.1.

For example at a infiltration pond in Berlin (Germany) temperature and stable water isotopes of water were used to estimate average travel times in the subsurface (Greskowiak et al., 2006). The authors determined the thermal retardation factor of approximately 2.1.

Sheets et al. (2002) investigated travel times by using EC and temperature at a riverbank filtration site in Cincinatti (USA). The authors do not report about thermal retardation.

Table 3: Heat transport features.

MAR site	Temperature Signal	Thermal retardation factor	References
St. Andre (Belgium), dune infiltration	Seasonal fluctuations, large differences between summer and winter	1.5 – 2.1	Vandenbohede and Van Houtte (2012)
Berlin-Tegel (Germany), infiltration basins	Seasonal fluctuations, large differences between summer and winter (amplitude ~25 °C, pore water velocity 2.5 m d^{-1}, travel time 50 d)	~ 2.1	Greskowiak et al. (2006)
Cincinatti, Ohio (USA), IBF	Seasonal fluctuations, large differences between summer and winter (amplitude ~30 °C in the river, short travel times)	Not reported	Sheets et al. (2002)

IBF = induced bank filtration;

3.4 Gases (e.g. ^{3}He, ^{3}H, SF$_6$, Xe)

Tritium (^{3}H or T) is a radioactive isotope of hydrogen with a half-life of 12.43 years. Anthropogenic tritium was emitted during thermonuclear bomb testing and was monitored in atmospheric fallout since the 1950´s (Clark and Fritz, 1997).

Chlorofluorocarbons (CFCs) and sulphur hexafluoride (SF$_6$) are anthropogenic substances introduced to the environment since the early 1930s and late 1970s respectively and are useful for dating groundwater less than 50-60 years old (Darling et al., 2012; Gooddy et al., 2006).

Darling et al. (2012) give a good general overview for using gas tracers (SF$_6$, CFCs) and state that sampling as described by IAEA (2006) is straight forward. The authors reported that SF$_6$ is chemically conservative in saturated porous media, but significant loss and retardation was observed under unsaturated conditions (Darling et al., 2012).

In MAR systems Clark et al. (2005) used SF$_6$, ^{3}He and noble gases at the El Rio (USA) surface spreading site which is characterized by relative high infiltration rates (~4 m/day) and moderately deep water table below ground level (not specified). The authors demonstrated that the travel time between the recharge locations and wells can be determined reliable by using gas tracers.

Clark et al. (2004) used T/^{3}He along with stable isotopes of water (δ^{18}O, δ^2H) and various isotopes of Xenon at an surface spreading site in Orange county (USA). In this study gas tracers showed conservative behavior (no losses, not retarded) under the local conditions.

In an infiltration pond experiment, Heilweil et al. (2004) used dissolved He and Br tracers to evaluate the effect of entrapped gas on hydraulic properties below an infiltration pond. The authors state that because of its low water solubility, He is preferentially found in the entrapped gas phase. Compared to the conservative transport of Br, the He signal is found to be retarded by a factor of 12. Both tracers were introduced artificially to the pond and results indicated that 7-26 % of porosity below the pond was filled with gas, thereby reducing the hydraulic conductivity substantially. The authors conclude that the periodic drying of pond bed sediments (tilling) may be replaced by wet tilling to minimize introduction of trapped gas.

McDermott et al. (2008) used SF$_6$ and T/^{3}He (deliberate and intrinsic, respectively) to examine groundwater travel times to wells within 150 m distance to spreading basins in Montebello Forebay (USA). The authors compared travel times derived from tracer tests with calculated travel times based on Darcy´s law. Under the local conditions the authors found that the initial arrival of the SF$_6$ signal and Darcy´s law calculations were in good agreement in the unconfined aquifer, but in the (semi-) confined aquifer SF$_6$ initial arrival times are significantly shorter than the mean Darcy travel times. This discrepancy is explained by preferential flow paths through discontinuities in the confining clay layers. Apparent ages calculated from T/^{3}He signal revealed the existence of older (some decades) and younger (<2 years, from the spreading basins) flow components in the recovery wells. This was explained by mixing of groundwater from several flow paths in the recovery wells due to long filters screens. The authors concluded that the conjunctive use of multiple tracers together with hydrogeological derived travel times improved the hydraulic understanding significantly.

At two bank filtration sites in Berlin (Germany) Massmann et al. (2007) used, among other tracers, Tritium/^{3}He and ^{4}He to evaluate travel times. The study revealed the existence of decades old deep flow component. Most important findings of gas tracer experiments during managed aquifer recharge are summarized in Table 4.

Table 4: **Gas tracer experiments during managed aquifer recharge.**

Tracer	Site and test description	Observed behavior	References
SF_6, Tritium/^{3}He	Montebello Forebay (USA), deliberate and environmental test at spreading basins	Results in good agreement to hydrogeological calculations for the unconfined aquifer, but in semi-confined aquifer mean travel times derived from tester tests are significantly shorter	McDermott et al. (2008)
SF_6, ^{3}He	Spreading basins, El Rio (USA), infiltration rate ~ 4 m/d, moderately deep water table (not specified), deliberate test	No significant retardation or loss of SF_6 in unsaturated zone observed	Clark et al. (2005)
Tritium/^{3}He, δ^{18}O, δ^2H, isotopes of Xe	Orange county (USA), deliberate and intrinsic test at spreading basins	Xe neither retarded nor lost in unsaturated zone	Clark et al. (2004)
^{3}He, Br	Sand Hollow (USA), ~20 m depth-to-water-table, deliberate test at spreading basins	^{3}He strongly retarded due to partitioning in gas phase	Heilweil et al. (2004)
Tritium/^{3}He, ^{4}He	Two bank filtration sites in Berlin (Germany), intrinsic tracer test	travel-time evaluation achieved by combining time-variant tracers (δ^{18}O, δ^2H and persistent wastewater residues) with Tritium/^{3}He age dating	Massmann et al. (2007)

3.5 Organic trace compounds (e.g. carbamazepine)

Pharmaceutically active compounds (PhACs) and other organic compounds of anthropogenic origin are often encountered in the environment. PhACs may enter the environment through various pathways, such as land fill seepage, manure fertilizers or discharge of treated effluent.

Cary et al. (2013) investigated the influence of sewage in an coastal aquifer in Cap Bon (Tunisia). The aquifer is used for artificial recharge through infiltration ponds fed with treated effluent in order to counteract seawater intrusion. The influence of the infiltration ponds, but also salinity ingress and other hydrochemical processes were evaluated by a set of tracers (i.e. $\delta^{11}B$, Cl, B, and CBZ). The authors were able to identify different sources (i.e. formation water, seawater, treated effluent, and natural groundwater recharge) on aquifer scale.

Pharmaceutical residues (e.g. phenazone-type pharmaceuticals) were used to identify that the source of the decade-old groundwater was originally surface water and therefore bank filtrate (Massmann et al. (2007)).

During bank filtration a shock load of chlorinated hydrocarbon (1,2- dichloromethane) in the river resulting from a chemical spill was also used to evaluate travel time from the surface water to the production well (Schmidt et al., 2003). 1,2-dichloromethane is characterized by a low sorption capacity and relatively high water solubility, but also retardation is reported in several studies (e.g. Wilson et al. (1981)). Therefore, the substance is not an ideal tracer and should be used only as a rough proxy for estimating travel time. The most important findings of using organic compounds as tracers during managed aquifer recharge are summarized in Table 5.

Table 5: Organic trace compounds

Tracer	Site and test description	Observed behavior	References
Gd_{excess}, CBZ, phenazone type residues	IBF in Berlin (Germany), intrinsic tracer test	Decade old flow component during IBF identified	Massmann et al. (2007)
1,2- dichloromethane, from chemical spill in the 1980´s	IBF at Rhine River (Germany)	Retardation, not conservative	Schmidt et al. (2003)
CBZ	Cap Bon (Tunisia), SAT	Groundwater sources on aquifer scale identified	Cary et al. (2013)

SAT = soil aquifer treatment; ASR = aquifer storage and recovery; IBF = induced bank filtration; CBZ = Carbamazepine

4 Summary and conclusions

Compared to deliberate tests, the use of intrinsic tracer experiments has the following advantages:

- Environmental tracer tests do not require spiking of source water, which simplifies logistics and avoids legal constraints (Kloppmann et al., 2009)

- Environmental tracer tests can be used over longer periods of time (Kloppmann et al., 2009)

The considered gas tracers can be useful in MAR systems with an already advanced conceptual understanding of the hydraulic behavior. Especially if "old" flow components are suspected, the use of gaseous tracer can be useful. If flow pattern is suspected to be more complex, other tracers (e.g. T/^{3}He) may reveal "old" flow paths and lead to improved hydraulic understanding of the site. Analysis of SF_6 are, compared to T/^{3}He analysis (~ 500 € per sample), more cost effective but not cheap (150 – 200 € per sample). Attention should be paid to MAR systems with thick unsaturated zone below the area of recharge, which may cause substantial losses and retardation of SF_6.

Due to relative large analytical errors in determining T/^{3}He and CFCs are not suitable to resolve short travel time less than 2 years. However, they can be useful to identify older flow components in the range of decades (e.g. Massmann et al. (2007)) or large scale flow features with a spatial extent of a few kilometers (e.g. Clark et al. (2004)).

Long-screened wells renders travel times measurements inappropriate, due to mixing of water with different ages (Clark et al., 2004).

Dye tracing (e.g. rhodamine, uranine) is commonly used in hydrology and karst hydrogeology, but rarely found during MAR (Bekele et al., 2008).

In SAT systems or MAR systems with certain degree of treated effluent, sewage-derived water constituents (e. g. B, Cl, Na and to some extent also SO_4) may be used as tracers.

Considering the large number of MAR sites it seems obvious that stable isotopes of water (δ^{18}O, δ^2H) are still underutilized for determing the sites' hydraulic properties. Stable isotopes of water are relative cheap tools (~10-20 € per sample) for identifying residence times and mixing between native groundwater and source water by using time series analysis.

The use of heat as a tracer has several advantages compared to hydrochemical tracers. Temperature is inexpensive, easy and a robust parameter to measure. In contrast to chemical tracers, no laboratory analysis is required and the data is available immediately. However, thermal retardation factors (usually: 1.4 – 2.1) are sediment specific but only show low variability compared to the hydraulic soil and aquifer conductivities.

Finally, a multi-tracer approach (≥ 2 tracers) is always recommended, because an ideal tracer is rarely found. A reasonable combination is at least one conservative tracer (e.g. stable isotopes of water) with a retarded tracer (e.g. temperature) to evaluate short travel times from the point of recharge (e.g. riverbed or pond) to the recovery well.

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