Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

Deliverable 6.1a

Database of groundwater age indicators and age distributions for vulnerability classification and sustainability assessments

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This report is part of a project that has received funding by the European Union's Horizon 2020 research and innovation programme under grant agreement number 731166.

Deliverable Data		
Deliverable number	D6.1a	
Dissemination level	Public	
Deliverable name	Database of groundwater age indicators and age distributions for vulnerability classification and sustainability assessments	
Work package	WP6,	
Lead WP/Deliverable beneficiary	GEUS	
Deliverable status		
Submitted (Author(s))	25/10/2021	Klaus Hinsby
Verified (WP leader)	25/10/2021	Klaus Hinsby
Approved (Coordinator)	26/10/2021	Laurence Gourcy

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DEFINITIONS AND CONCEPTS OF GROUNDWATER AGE, VULNERABILITY (SUSCEPTIBILITY) AND SUSTAINABILITY

Abbreviations and acronyms
GAD = Groundwater age distributions
RTD = Residence time distributions
TTD = Travel time distributions

On the use of the term "groundwater age"
Some authors recommend to abandon the use of "groundwater age" and "mean groundwater age" as it is misleading in many settings (Troldborg et al. 2008; Suckow 2014). We still believe though that "groundwater age" is a useful term for the general understanding of groundwater aging and travel times along flow paths in the subsurface. By using the term groundwater age distribution we imply that groundwater age and travel times vary in time and space in the subsurface and that groundwater collected from even quite small screens is a mixture of groundwater with different age (or travel time) that may vary between a few years in short shallow screens (< 10 cm) and up to thousands of years or more in wells with long screens (>> 10 m), which e.g. short cuts separate aquifers.

Here we assume groundwater age distributions (GAD) = residence time distributions (RTD) = travel time distributions (TTD) and use the terms as synonyms. The "mean groundwater age" is an "apparent age" potentially covering a wide range of mixed ages, which may be misleading, when assessing the vulnerability of a well or a groundwater body towards pollution etc. Hence, we strongly recommend the use of multiple tracers and models that enables the simulation of age distributions for a specific monitoring or water supply well. Simulation of groundwater age distributions based on measurements of multiple tracers such as ^{3}H, ^{39}Ar and ^{14}C and/or well calibrated groundwater flow models preferably calibrated on the contents of dating tracers, gives a much better understanding of the vulnerability of a well or an aquifer towards pollution from the surface than the mean age.

"Vulnerability" or "Susceptibility" of aquifers and water supply wells towards pollution from the surface
In this report we generally use the terms groundwater "vulnerability" "susceptibility" as synonyms defined as "the tendency or likelihood for contaminants to reach a specific position in
the groundwater system" (Solder et al., 2020). Groundwater containing tritium (^{3}H) or other indicators of modern (post-development) such as industrial gases e.g. CFCs, SF_6 (Hinsby et al., 2001; Jurgens et al., 2016) recharged the aquifers later than approximately 1950 and often contains contaminants such as nitrate and pesticides. Hence such water types are considered at high risk of pollution from the surface and having high vulnerability / susceptibility.

The absence of tritium (^{3}H) and other age indicators like mainly ^{39}Ar or ^{14}C on the other hand indicate paleowaters older than 10.000 years with no or very little risk of pollution from the surface (low vulnerability). Poorly developed or damaged water supply wells may though always be at risk of pollution from the surface. In addition paleowaters have increased risk of elevated salinity and concentrations of harmful geogenic elements.

Groundwater containing no ^{3}H but ^{39}Ar and ^{14}C have ages with the age range of > 70 and < 10.000 years. This may be considered the "sweet spot" for water supply with little risk of contamination from the surface and limited risk of elevated geogenic elements in most aquifer systems.

Aquifers, well fields and even single water supply wells with long screens may contain all the three water types or age classes mentioned above. In some cases e.g. at supply well or well field scale, a more detailed classification based on estimated groundwater ages is often warranted in order to get a better understanding of the susceptibility of a given water supply well or well field (Broers et al., 2021a, b; Solder et al., 2020) or the history and fate of observed pollutants in the subsurface (Jakobsen et al., 2020). This will e.g. enable a more detailed ranking of the risk of pollution of water supply wells.

"Vulnerability" of groundwater quantity / sustainable use of groundwater resources

Aquifers / groundwater samples without or low ^{14}C concentrations (e.g. < 1 pmc - but depends on geochemical reactions in the aquifers) is considered to be paleowaters, older than 10.000 years. These groundwaters recharged during the late Pleistocene typically the last stages of the latest glaciation, and such waters may be considered vulnerable to overexploitation (unsustainable use) as they potentially are recharged at a very low rate. They are furthermore at risk of containing relatively high concentrations of e.g. chloride and geogenic trace elements potentially affecting human health. An old groundwater age of a single well itself, however, is not a good indicator for unsustainability, the distribution of groundwater ages in an aquifer or aquifer system provides a much better indication of the risk of overexploitation and sustainable use of the aquifers (Ferguson et al., 2020).

Groundwater recharged during the Pleistocene (Edmunds et al., 2001; Hinsby et al., 2001a) is basically non-existing in Canada, North America and Northern Europe at the glacial maxima e.g, around the last glacial maximum (LGM) about 18 ka BP (Beyerle et al., 1998, Edmunds and Smedley, 2000). At the LGM thick permafrost covered most parts of Northern Europe and America efficiently hindering groundwater recharge. During ice sheet advances groundwater recharge was most probably highly varying ranging from limited (Edmunds and Smedley, 2000) to an order of magnitude higher than present day recharge (Person et al., 2007). High quality meltwaters from perhaps several glacier advances in the latest glaciation are, however, found and exploited in present day aquifers e.g. in Northern Europe (Pärn et al., 2019, Vaikmae et al., 2021).

Sustainability

´The UN Sustainable Development Goals and the European Green Deal has a very strong focus on sustainability. The current use of water is not sustainable in many places in Europe and globally, and calls for: *"a new framework for analysing and establishing limits to a variety of human modifications of the water cycle"* (Gleeson et al., 2020). This is required to protect society and nature and keep the earth within "Planetary Boundaries" and a "safe operating space for humanity" (Rockström et al., 2009; Steffen et al., 2015).

Hence, in concrete terms, as groundwater is the largest freshwater resource and an important part of the hydrological cycle, groundwater governance and management has to be sustainable protecting both groundwater quantity and quality to ensure sufficient future water resources for water supply, food production and ecosystems. Understanding groundwater age distributions of aquifers and well fields is a prerequisite for protecting the groundwater resources quantity and quality e.g. by enabling assessments of groundwater recharge, transport, history and fate of pollutants, and the sustainability of groundwater abstraction, globally.

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1. INTRODUCTION

1.1 Background and history of tracer applications for assessment of groundwater age distributions in research and management projects

Estimation of groundwater age, travel or residence time distributions by environmental tracers and/or models has become an increasingly important tool for study of groundwater flow and transport in aquifers and aquitards since the concept and potential of using tritium (^{3}H) and ^{14}C for groundwater dating was suggested e.g. by Kaufman and Libby (1954); Eriksson (1958) and Münnich and Vogel (1959). Later, many different environmental tracers have been introduced and applied for groundwater dating in different age intervals (Figure 1, 4 and 5).

Since the introduction of the isotope tracers for estimation of groundwater travel times many studies were conducted at local and short time scales with tracers for dating of young groundwater (Andersen and Sevel, 1974; Hinsby et al., 2001; Broers et al., 2004; Troldborg et al., 2008, Gourcy et al., 2009, Newman et al. 2010; Kivits et al., 2018; Jakobsen et al., 2020) as well as at regional scales with long travel times with tracers for dating of old groundwater e.g. in the East Midlands aquifer (Andrews and Lee, 1979) and the studies in large European basins such as the London Basin (Smith et al., 1976); the Madrid Basin (Llamas et al., 1982), the Great Hungarian Plain (Stute et al. 1992) and the Paris Basin (Marty et al., 1993). European studies furthermore demonstrated that paleowaters more than 10.000 years old with paleoclimate signals are found in many aquifers across Europe (Edmunds et al., 2001, EGDI-HOVER WP6, 2021).

Industrial gases such as CFCs (chlorofluorocarbons) and SF_6 were later introduced for groundwater dating of young groundwater affected by human impacts (Busenberg and Plummer, 1992, 2000; Hinsby et al., 2001; Newman et al., 2010) although these became less applied primarily because of degradation of the CFCs in anoxic aquifers (Hinsby et al., 2007) and for SF_6 due to terrigenic sources or contamination in urban environments (Busenberg and Plummer, 2008).

For this report we focus on primarily the radioactive isotope tracers as these seem to be more robust and widely applied than the industrial gases.

Besides improving our understanding of groundwater travel times and groundwater flow and mixing in the subsurface in different types of aquifers (Eberts et al., 2012), groundwater dating is used for assessment of the advance of modern potentially polluted groundwater and the susceptibility / "vulnerability" of water supply wells towards pollution from the surface (Hinsby et al., 2001, 2008; Broers, 2004; Manning et al., 2005; Eberts et al., 2012; Visser et al., 2013; Jurgens et al., 2016; Kivits et al., 2018), and the assessment of trends and history of specific contaminants such as nitrate (Bohlke and Denver, 1995; Hansen et al. 2012, 2019, Jurgens et al., 2016), pesticides (Visser et al., 2013, Jakobsen et al., 2020) and veterinary pharmaceuticals (Kivits et al., 2018).

Environmental tracers and model simulations may also be used for the estimation of flow in the unsaturated zone and groundwater recharge (Edmunds and Tyler, 2002¸ Engesgaard et al., 2004; Scanlon et al., 2006).

For the estimation of groundwater ages in short (< 1m) and shallow screens in relatively homogeneous aquifers a mean age or travel time to a specific point using the assumption of piston flow is a reasonable approximation (Plummer et al., 1993) as the age distribution around the mean is rather narrow. For long-screened wells screened or open in potentially several different aquifers or in fractured rocks such an approximation generally does not hold (Broers et al., 2021a,b). In such cases an estimation of the groundwater age distributions either by groundwater flow and transport models or by the use of a range of environmental tracers suited for dating of groundwater of different age is of much more value (Troldborg, 2004; Bethke and Johnson, 2008, Troldborg et al., 2008; Eberts et al., 2012, Jakobsen et al., 2020).

Currently, data on groundwater age indicators cannot normally be obtained from common databases or repositories, but only through papers and reports, and spreadsheets available to a limited number of researchers. Generally national groundwater databases in Europe tore limited information on a few groundwater age indicators primarily tritium (^{3}H), but not the new indicators such as ^{39}Ar and ^{85}Kr. As the authors foresee increasing applications and an increasing amount of multiple tracer studies, which will enable more advanced analyses of groundwater age and travel time distributions, we believe it is time to ensure that data on as many environmental tracers as possible are stored in common databases or repositories with easy access for relevant stakeholders.

Common repositories storing the increasing amount of valuable environmental tracer and age indicator data including model simulation of age distributions, are required to ensure easy and FAIR1 data access. This is required to ensure easy combination of data on groundwater age distributions with groundwater quality data e.g. to assess the history and fate of groundwater pollutants (Jakobsen et al., 2020) and to improve our understanding of the groundwater flow systems.

This report initiates and briefly introduces a new European simple database developed within the GeoERA HOVER project that enables the storage of concentrations of all the environmental tracers currently used for groundwater dating and simulation of groundwater age / travel time distributions covering the age range between a few years and up to > 25.000 years. An age range covering the ages of most of the exploited groundwater resources in Europe (see e.g. Fig. 3). Storage of environmental tracers for dating of very old groundwater up to 1 Ma or more is also possible. The relevant data can be uploaded to the European Geological Data Infrastructure (EGDI) in simple tables in the Geopackage format. Access to examples of groundwater age indicators measured in aquifers, monitoring, remediation and water supply wells will be provided via map viewers on EGDI from where data can also be downloaded.

1 Wilkinson M, Dumontier M, Aalbersberg I (2016) The FAIR Guiding Principles for scientific data management and stewardship. Sci. Data 3 (2016). Sci data 3:1–9

1.2 Estimation and visualisation of groundwater age distributions and vulnerability towards pollution from the surface

The groundwater travel time and age distribution in the aquifer systems have significant implication for the advance of modern potentially polluted groundwater (Hinsby et al., 2001), the vulnerability of aquifers towards pollution from the surface (Fig. 1, Manning et al., 2005; Solder et al., 2020) and the risk of over-abstraction (Ferguson et al., 2020) or elevated salinity or concentrations of potentially harmful naturally dissolved elements. Hence, information on and a sound understanding of groundwater flow dynamics and age distributions are of huge importance for sustainable groundwater management in general.

The post-development groundwater system in Fig.1 with groundwater ages less than hundred years that typically contains measurable tritium (^{3}H, Fig. 4 and 5) is at high risk of pollution from the surface, while the deeper pre-development groundwater system, which do not contain tritium and no or very low concentrations of ^{39}Ar, may contain elevated and increasing concentrations with increasing age with positive or negative health impacts depending on the element and the concentration level. The concentration of some of these elements may serve as relative age indicators (Edmunds and Smedley, 2000). The window between these two i.e. with groundwater ages typically within the age range of 100 - 1000 years seem to be an optimal window for groundwater abstraction for water supply. It is, however, very important to note that persistent pollutants advance deeper and deeper into European aquifers (Hinsby et al., 2001), and that it is very important to protect shallow groundwater resources towards pollution from the surface to protect this valuable and renewable resource and ensure continuous exploitation of the resource in a sustainable way.

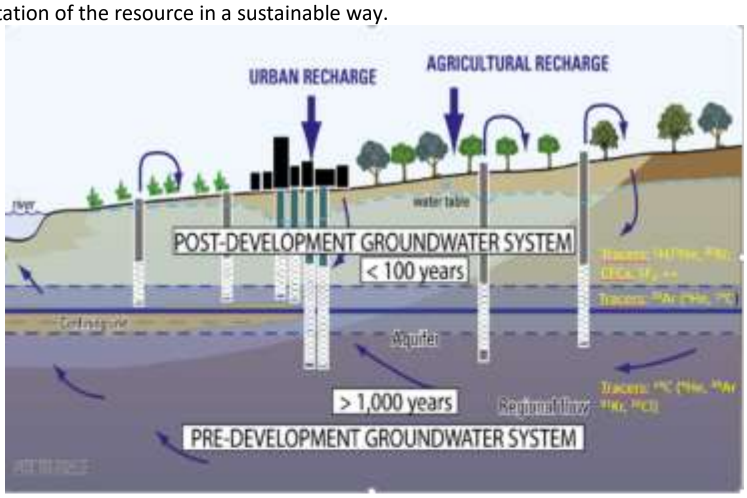

Figure 1. Simplified conceptual model of the age structure of a regional aquifer, mixing of groundwater of different ages in long-screned wells etc. Tracers highlighted in yellow indicate the most common tracers applied for groundwater age and travel time distributions in different parts of aquifer systems. Modified after Jurgens et al. (2016).

While Figure 1 demonstrate overall and general groundwater age distributions in aquifer systems, Figure 2 demonstrate detailed groundwater age distributions in the bottom and top of a water supply well with a 12 m long screen. Both age distributions simulated based on measured multiple dating tracers ($^3H/^3He$, ^{85}Kr, ^{39}Ar and ^{14}C) with TracerLPM (Jurgens et al., 2012, 2016), red curves, and particle tracking (Jakobsen et al., 2020), blue curves indicate that significant parts of the pumped water from the top of the well is younger than / recharged since 1995, while the water pumped from the bottom of the well is all older than 1995. This information has important implications for the assessment of the history and fate of the pesticides observed in the top and bottom of the water supply well (Jakobsen et al., 2020).

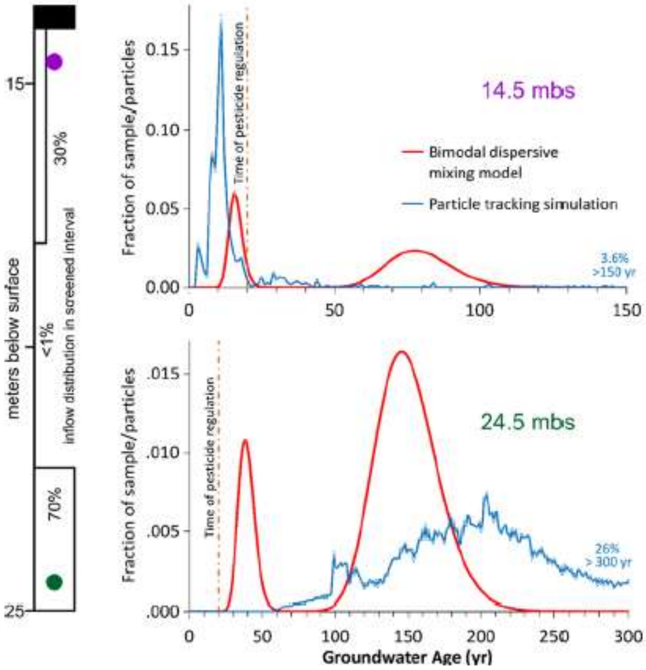

Figure 2a. Example of simulated age distributions based on measured tracers (red) and particle tracking with groundwater models (blue) in the top and bottom of a water supply well contaminated with pesticides (Jakobsen et al., 2020). Note that the central part of the screen provide less than 1 % of the inflow to the well.

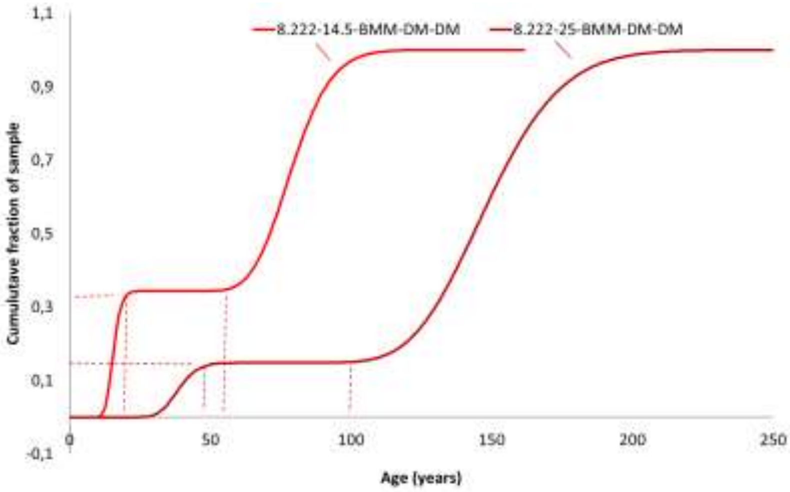

Figure 2b. Cumulative Density Functions (CDF, Appendix C) / cumulative fractions of groundwater age for the top (to the left) and bottom (to the right) samples shown in Figure 2a.

The benefit of visualizing groundwater age distributions in water supply wells as shown in Figure 2a i.e. as probability density functions of age is that the mean ages of the young and old groundwater fractions are easily observed – i.e. 16 and 80 years, respectively, for the top sample and 39 and 150 years for the bottom sample.

The benefit of visualizing groundwater age distributions as in Figure 2b i.e. as a cumulative distribution function (plot of the cumulative fraction of a sample younger than a given age) is that the fractions of the young and old water types is easily observed. In the top (left) sample in Figure 2b about 33 % of groundwater pumped from the top of screen is less than 20 years old while the rest (about 67 %) is older than 50-55 years old. At the bottom of the screen (right curve in Figure 2b) all groundwater including the young fraction is older than 20 years – 15% is less than about 50 years old, and 85 % is older than about 100 years.

Hence a pesticide found in the top of the well has infiltrated from the surface after the pesticide regulations were introduced in 1995 (about 20 years before the sampling, Figure 2a, Jakobsen et al., 2020). In contrast another pesticide found in the sample pumped from the bottom of the well infiltrated before the pesticide regulations in 1995 (Jakobsen et al., 2020).

Figure 3a, b and c below represent details somewhere between the conceptual model of Figure 1 and the detailed simulations of groundwater age distributions in the top and bottom of a water supply well shown in Figure 2a and 2b. Figure 3a show the location of the pilot study area (The Roer Valley Graben) with many well fields in the Netherlands close to borders with Belgium and Germany, and Figure 3b and c illustrates age distributions of the well fields as grouped in five different age groups in 1) Cross sections through the Roer Valley graben (Figure 3b) and 2) an overview of the defined age classes pumped from the 39 investigated wells fields (Figure 3c).

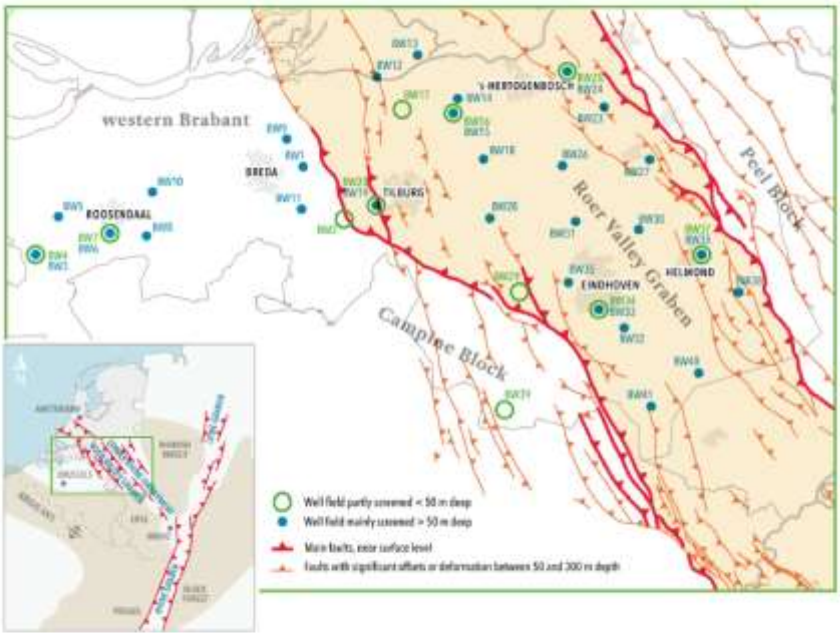

Figure 3a. Map of the study area in the Netherlands, the Roer Valley Graben, close to borders with Belgium and Germany with location and depth of the sampled well fields (Broers et al., 2021a).

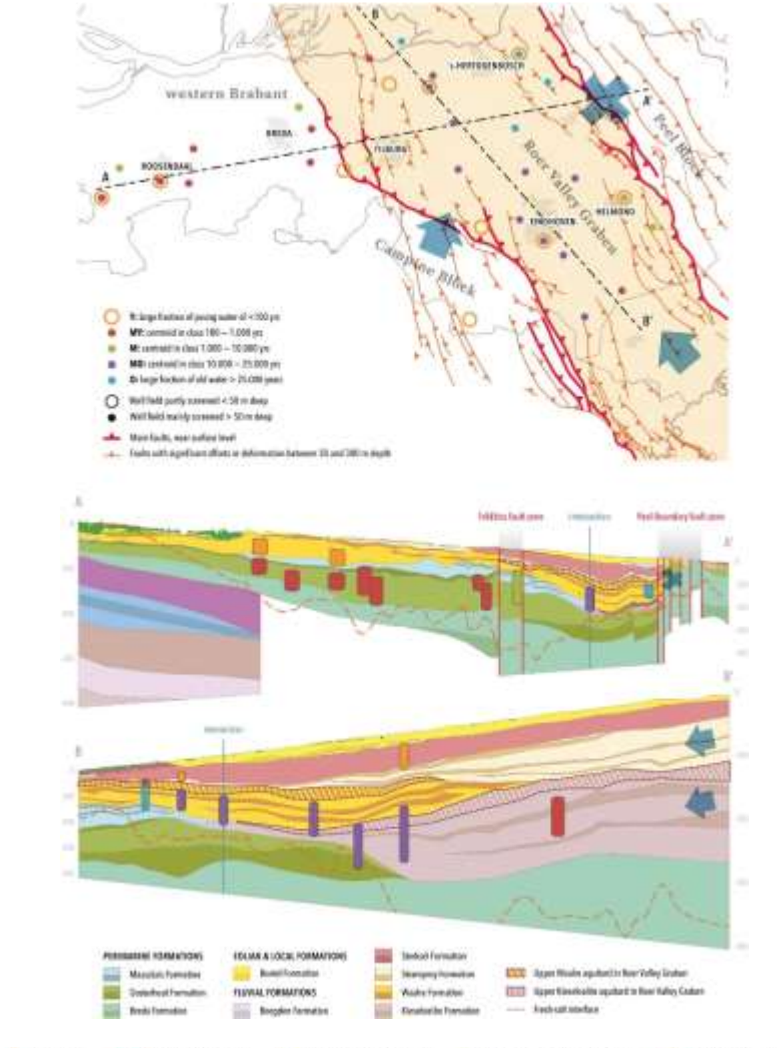

Figure 3b. Groundwater age distributions in groundwater from 39 public water works abstracting water from well fields in aquifers systems of the Roer Valley Graben, The Netherlands (Broers et al., 2021a, b).

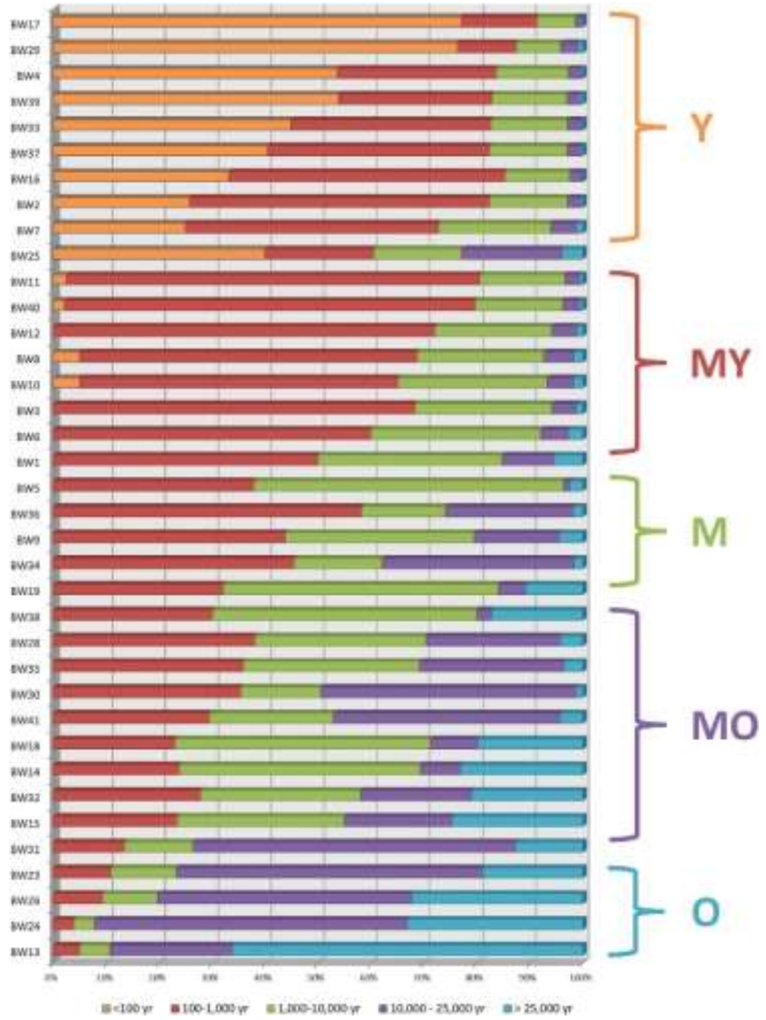

Figure 3c. Groundwater age distributions in 39 public water works abstracting water from the Roer Valley Graben aquifer system shown in Figure 3a, The Netherlands (Broers et al., 2021a, b).

For advanced applications, calculation and simulation of groundwater age distributions the tracer databases need to store not only the age indicators themselves, but also supporting tracer information and parameters such as recharge elevation and temperatures. Further, the estimated age distributions and the information on groundwater vulnerability/susceptibility to be gained from these should be stored and accessible too. Hence, the developed databases should enables the following important information to be stored and accessed for advanced management of wells fields and groundwater systems in general:

1) Groundwater age indicators measured in groundwater monitoring and water supply wells: $^{3}H/^{3}He$; ^{85}Kr, ^{39}Ar, ^{14}C, CFCs, SF_6, ^{4}He etc. (Appendix B)

2) Supporting parameters e.g. groundwater recharge temperature and elevation, and parameters used for correcting for the effects of subsurface processes such as excess air and carbonate dissolution, noble gases and $\delta^{13}C$, respectively, etc. (Appendix C)

3) Age distributions computed as e.g. probability density functions and cumulative density functions by lumped parameter models such as TracerLPM enabling assessment of groundwater vulnerability and calculation of a susceptibility index (Solder et al., 2020) and easy plotting and visualisation of the age distributions as e.g. shown in Figure 2a, b and Figure 3 a, b and c. (Broers et al., 2021a, b; Jakobsen et al., 2020, Appendix C).

4) Age distributions computed as probability density functions and cumulative density functions by groundwater flow models (e.g. Troldborg et al., 2008, Eberts et al., 2012) enabling calculation of a susceptibility index and easy plotting and visualisation of the age distributions and mean ages similar to and for comparison with the results calculated in 3) (Jakobsen et al., 2020; Jurgens et al., 2016; Solder et al., 2020)

5) Easy comparison of age distributions obtained by lumped parameter models (3) and groundwater flow models (4) e.g. by common plots of the age distributions obtained by the two methods (Appendix C)

6) Simple indication of the vulnerability / susceptibility of the investigated wells and aquifer system towards pollution from the surface based on the contents of the measured tracers or the fraction of young water and/or the computed susceptibility index as simulated by groundwater flow models. For easy and fast overview on Pan European maps we suggest – three different classes – 1) groundwater < 100 years – high vulnerability / risk of pollution (suggested colour = red) 2) groundwater > 100 – 10.000 yr low vulnerability (suggested colour = green) and 3) very low vulnerability (suggested colour = purple), see deliverable D6.1.b.

Very low vulnerability does not mean that pollution is impossible. Pollution may always occur in poorly developed wells or if the well casings are damaged etc.

The contents of the database incl. parameters, units, derived / computed age distributions, vulnerability/susceptibility to pollution from the surface and standards for data reporting is described in the following.

2. ENVIRONMENTAL TRACER DATA POTENTIALLY INCLUDED IN THE EUROPEAN DATABASE OF AGE INDICATORS

2.1 Environmental tracers used for estimation of groundwater ages in the age range < 1 - > 1 million years

There is a wide range of environmental tracers, which are applied for estimation of groundwater age and travel time distributions at small and large spatially scales or young and old temporal scales. General descriptions of the methods may be found in e.g. Cook and Herczeg (2000) and Kazemi et al. (2006), while research needs on the methods can be found in Newman et al. (2010). The value of understanding groundwater age and travel time distributions in the subsurface both for groundwater research and management is widely accepted and the application of groundwater dating tracers and/or modelling for simulation of groundwater age and travel time distributions are receiving increasing attention across the world (Sprenger et al., 2019).

Recently the application of multiple tracers providing information for different groundwater age intervals, the simulation of the fraction of these and the susceptibility of e.g. water supply wells were demonstrated in several studies (Broers et al., 2021a, b, Hinsby et al., 2021, Jakobsen et al., 2020, Jurgens et al., 2016, Kivits et al., 2018, Solder et al. 2020; Wright et al., 2021).

Figure 4 shows the most common environmental tracers used for estimation of groundwater age or travel time distributions for groundwater recharged to the aquifers less than 10 years to more than 1.000.000 of years ago.

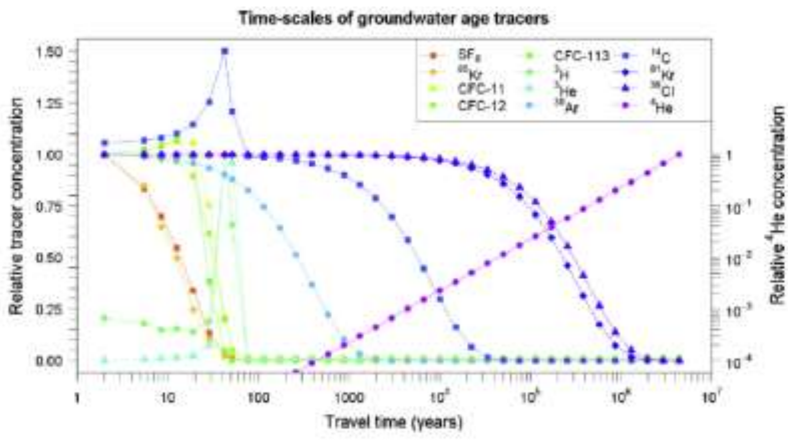

Figure 4. Diagram showing the relative tracer concentrations in groundwater of tracers used for groundwater dating in the different groundwater age intervals (Modified from Massoudieh et al., 2014).

Figure 5 illustrate the tracers used for dating groundwater in different age intervals as well as the analytical methods used for the analysis of the different tracers. The use of different tracers for dating of different age intervals provides additional valuable information e.g. for identification of mixing of different water types with different groundwater age.

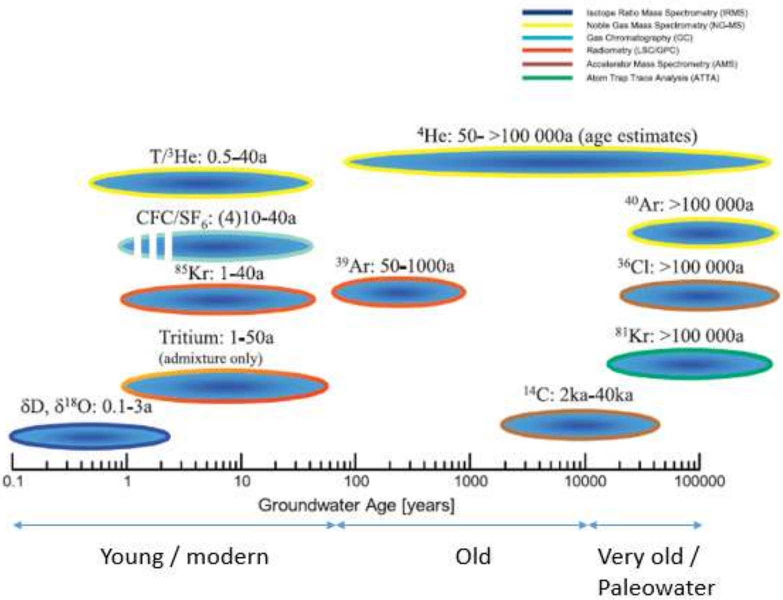

Figure 5. Age intervals and methods for the analysis of environmental tracers used for groundwater dating (modified after Suckow, 2014) including example of three age groups: young, old and very old (paleowater) groundwater. These age groups may be easily visualized on regional maps based on groundwater tracer contents e.g. in red, green and purple colours for young, old and very old groundwater.

The new European database for groundwater dating tracers accept concentrations and information on all of the environmental tracers illustrated in Figure 4 and 5 as well as the supporting parameters needed for estimation of groundwater ages such as mean annual recharge temperatures, elevation, noble gases and stable isotopes, time of sampling and analysis etc. (Table 1, Appendix B and C). Note that the indicated age intervals in Figure 5 may be extended for some of the tracers (e.g. ^{4}He and ^{39}Ar) – the age range indicate only roughly the potential groundwater dating intervals. The measurements of multiple tracers enable simulation of the mixing of groundwater types with different age and hence groundwater age distributions in the sample (Figure 2 and 3, Jakobsen et al., 2020; Solder et al., 2020; Broers et al. 2021a, b).

2.2 Environmental tracer data, metadata and data formats required for upload to EGDI

Environmental tracers and age indicators such as ^{3}H, ^{39}Ar and ^{14}C listed in Table 1 can be reported to the EGDI information platform if basic meta data concerning the data have been uploaded to the spatial metadata catalogue "MicKa" beforehand.

Table 1. Example of environmental tracer data for groundwater dating required for upload to simple EGDI tracer database[1, 7] accessible via map viewers on the European Geological Data Infrastructure (EGDI)

Well[2] ID	X[3]	Y[3]	Z[4] (masl)	Screen[5] Depth (m)	Screen Length (m)	Year of sampling	^{3}H	^{3}Hunit	^{3}Herror	^{39}Ar	^{39}Arunit	^{39}Arerror	^{14}C	^{14}Cunit	^{14}Cerror	+T4[6]
8.222-t	544167	6357128	6	13-15	12	2014	2.98	TU	0.21	98	pmAr	10		pmc		
8.222-b	544167	6357128	6	23-25	12	2014	4.42	TU	0.35	80	pmAr	10		pmc		

[1]The data has to be provided in the shown units and with decimal points as the decimal separator, preferably in Geopackage format https://www.geopackage.org/ - for other environmental tracers e.g. ^{85}Kr, CFCs, SF_6, etc. please use the units provided in the table in appendix B.
[2]Use your own well ID system,
[3]You can use your preferred coordinate system, but remember to include information on the system to enable potential conversion, in this case the coordinates are provided in UTM/ETRS89 ZONE 32 coordinates
[4]Elevation in meter above sea level (add – if below)
[5]To top of screen (meter below surface) – if nothing else is indicated it is assumed that the collected sampled is a mixed sample from the whole screen section – in this case we have sampled at the top of the screen (8.222-1) between 13-15 mbs and at the bottom of the screen at 23-25 mbs (8.222-b)
[6]You can add data on other environmental tracers you may have analyses for but please use the notation provided for the tracers in appendix 2 and remember to include relevant metadata in the Micka metadata catalogue.
[7]Relevant metadata e.g. supporting parameters for calculation of groundwater ages (recharge temperatures etc.), sampling techniques, laboratories, project websites, funding and related publications should be uploaded to the MicKa metadata catalogue

3. ENVIRONMENTAL TRACERS IN GROUNDWATER STUDIES - FUTURE PERSPECTIVES AND RECOMMENDATIONS – A GLOBAL OUTLOOK

The number of environmental tracers for investigation of groundwater flow dynamics and groundwater age and travel time distributions and the number of studies applying these are continuously increasing. Hence, there is a strong need for developing international standards for storing the tracers and provide easy and FAIR access (Wilkinson et al., 2016) to groundwater tracer data to facilitate data transfer and international collaboration. Databases should include and enable data upload from groundwater research projects, groundwater monitoring programs and well field investigations of e.g. the vulnerability of water supply wells towards pollution from the surface. Common standards and databases will improve and enable easy communication between groundwater scientists and managers, globally.

In the GeoERA HOVER project we have compiled results and information from more than 20 pilot studies on the application of groundwater dating tracers in groundwater research and management projects across Europe (Szocs et al., 2020), and made selected data and information from these available via the HOVER WP6 map viewer developed for the EGDI information platform in the GeoERA program (EGDI-HOVER-WP6, 2021). The provided information include selected tracer data from some of the investigated pilot areas in order to initiate common efforts and work towards establishing a comprehensive database that include harmonized data on environmental tracers in groundwater, which are used for assessment and simulation of groundwater age and travel time distributions and general assessments of groundwater sustainability and the evolution of the groundwater resources.

Such data and information are very important for protection and sustainable management of European groundwater resources protecting both legitimate uses (e.g. drinking water supply and irrigation) and biodiversity (groundwater dependent or associated terrestrial and aquatic ecosystems) according to the Water Framework Directive and the European Green Deal. They are furthermore important for and support UN policies such as UN sustainable development goals especially SDG6, 11 and 12: Clean water and Sanitation, Sustainable Cities and Communities and Responsible Consumption and Production, and for support of the new UNFC specifications for groundwater (UNECE, 2021) and the new UN Resources Management System, UNRMS (UN, 2021) . Finally, the data are very useful in trend assessment, design of monitoring systems, and assessment of lag times i.e. the response time of a certain measures or regulations before positive results appear in monitoring or water supply wells.

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We have therefore developed a simple upload procedure for all environmental tracers applied for groundwater dating as e.g. shown in Figure 4 and 5. The data is uploaded to EGDI (http://www.europe-geology.eu/) in the Geopackage file format, https://www.geopackage.org/. The Geopackage file may include metadata either embedded in the Geopackage file itself or in the EGDI metadata catalogue (MicKa) required for data interpretation and groundwater age simulations. Upload of data to EGDI is only possible after upload of metadata on the data to Micka, and data can only be uploaded to EGDI by registered users following specific procedures (EGDI, 2021). If this is not possible for the data providers, the data may be send to the first author of this report, and GEUS will upload the data following the required procedures. Examples of applied tracers (^{3}H, ^{39}Ar and ^{14}C) and selected metadata for the analysed groundwater samples were shown in Table 1 in section two of the report. New tracers appear occasionally, and the EGDI map viewer and repository of analysed environmental tracers therefore accept data and information on all such new tracers if units, metadata and tracer names following international standards are included in the geopackage file. The developed database is not only open to Europe, but data may be provided by countries outside Europe (globally), as long as the data is provided in common standards, and X, Y, Z coordinates are provided for the tracer data in standard coordinate systems. The EGDI is by default using EPSG:3034, which is the preferred coordinate system for Europe, but a world map can be set up in geographical coordinates if required.

The three tracers mentioned above are used for estimation of groundwater ages from within a few years to more than 25.000 years. The tracers may be used as indicators of groundwater susceptibility/vulnerability towards pollution from the surface (^{3}H) or of very old / paleowaters (^{14}C), which may constitute valuable strategic reserves. Paleowaters may though also be at risk of elevated concentrations of harmful trace elements and/or salinity or overexploitation. Radioactive isotopes with long half-lives of several hundred thousands of years such as ^{81}Kr and ^{36}Cl may in addition be used to date very old groundwaters in large basins of up to more than a million years. The data provided for the new European environmental tracer database include a few examples of datasets with ^{81}Kr concentrations or activities.

3.2 Environmental tracers, vulnerability / susceptibility, and sustainability assessments – options for international collaboration

In the current version of the tracer database developed in Geopackage format, and the associated map viewers and metadata catalogue, we have used a very simple groundwater vulnerability indicator based solely on the presence or absence of primarily the three tracers (^{3}H, ^{39}Ar and ^{14}C). Groundwater containing measurable ^{3}H in groundwater pumped from wells is considered vulnerable to pollution from the surface (red colour on map), groundwater containing measurable ^{39}Ar and/or ^{14}C > 10 pmc is considered Holocene (< 10.000 years old, green colour on map) and groundwater with < 10 pmc ^{14}C is considered > 10.000 years old or palaeowater (purple colour on map). Holocene and Pleistocene groundwater have low vulnerability to pollution from the surface.

The groundwater age range between 100 and 10.000 years may be considered the “sweet spot” for groundwater supply as the risk of pollution from the surface or elevated salinity or harmful trace elements is relatively low. It is, however, very important to protect the highly valuable shallow and young groundwater towards pollution from the surface as shallow water supply wells are easier and less costly to develop and exploit. In addition, some contaminants are very persistent and may advance to deep parts of the aquifer systems and hence pollute also deeper aquifers with time (Hinsby et al., 2001)

The vulnerability indicator based on the concentration levels of the tracers described above is very simple, and can be improved with new more detailed simulations of groundwater age and travel time distributions enabling calculation of more precise fractions of young and old water

(Visser et al., 2013, Jurgens et al., 2016, Jakobsen et al., 2020; Broers et al., 2021a, b) and a susceptibility index as e.g. recently developed and proposed by the USGS (Solder et al., 2020).

Hence, we envisage that future versions of the environment tracer database and the associated map viewer and metadata catalogue will be improved by more sophisticated and informative visualizations of groundwater age distributions and vulnerability e.g. as demonstrated in several recent studies (Broers et al., 2021a, b, Jakobsen et al., 2020, Solder et al., 2020). Future versions of the environmental tracer database should enable comparison of groundwater age and travel time distributions estimated by different tools including analytical lumped parameter models for simulating the measured concentrations of the environmental tracers and physically based groundwater flow models (as indicated in Appendix B and C). Finally, future databases should e.g. include calculated susceptibility indices and fractions of different groundwater age ranges calculated by the different tools (Appendix C).

The authors find environmental tracer data of immense value for groundwater research and sustainable management of groundwater resources, globally, especially in combination with groundwater flow models. We would therefore like to encourage the international groundwater research community in collaboration with international organizations such as the International Atomic Energy Agency (IAEA) to develop common global standardized databases and visualization tools for environmental tracers in the subsurface in a common effort similar to what the IAEA and other national and international organisations do for isotopes and gases in precipitation and the atmosphere. This could e.g. be a theme for an IAEA coordinated research program. Work on such a common database should preferably also include tools and indicators / indices for vulnerability / susceptibility and sustainability assessments based on environmental tracer data and groundwater flow models.

Sustainable use of (ground)water and subsurface resources is of increasing importance and it is imperative to comply with and support international policies including the UN Sustainable Development Goals and the European Green Deal etc. The importance of Environmental tracer data for aquifers and groundwater resources management has been recognized for decades and the subject of many international studies, globally, e.g. in IAEA coordinated research programs (IAEA, 2021). Such data will provide strong support to the UNFC specifications for groundwater, which is currently developed (UNECE, 2021) and the new UN Resource Management System (UN, 2021). The value of environmental tracers for sustainable groundwater management cannot be overestimated.

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APPENDIX A - GROUNDWATER AGE AND TRAVEL TIME INFORMATION IN WP6 PARTNER COUNTRIES

The questionnaire to the 14 HOVER WP6 partner countries (Austria, Cyprus, Croatia, Denmark, Estonia, France, Hungary, Malta, The Netherlands, Romania, Slovenia, Spain, Sweden and Ukraine) on the availability of measurements of groundwater age indicators and groundwater age distributions simulated by groundwater models, revealed that there are currently limited multiple tracer data available for European groundwater monitoring and water supply wells, and hence for a European tracer and groundwater age database (see below). However, there are use cases from most European countries applying one or two environmental tracers for groundwater dating, 23 of these were described in the HOVER deliverable D6.2 (Szocs et al., 2020). Link to use cases and pilot areas providing information and data on groundwater age distributions compiled in HOVER: Groundwater age study sites. The number of studies applying multiple tracers for simulation of groundwater age distribution in water supply and monitoring wells similar to studies by Visser et al. (2013), Kivits et al. (2018), Jakobsen et al. (2020), Broers et al. (2021a,b) and Hinsby et al. (2021) are anticipated to grow in the future.

APPENDIX A - TABLE OF GROUNDWATER AGE AND TRAVEL TIME INFORMATION IN EUROPE AVAILABLE FROM THE 15 HOVER WP6 PARTNERS ACCORDING TO A QUESTIONNAIRE CONDUCTED IN THE PROJECT.

Type of groundwater age information	Partners with available information from their country*	Comments
1. Tracer age distributions in aquifers corroborated by groundwater flow models or vice versa	BRGM (FR), CGS (CZ), GEUS (DK), MBFSZ (HU), HGI-CGS (HR), MTI (MT),	Other HOVER partners with such data: BGR (DE), BGS (UK), TNO (NL)
2. Groundwater flow models calibrated by groundwater age indicators	BRGM (FR), GEUS (DK), MBFSZ (HU)	
3. Calibrated groundwater flow models, which are able to simulate groundwater age distributions, but no groundwater age indicators / tracers to corroborate these ?	BRGM (FR), GEUS (DK), HGI-CGS (HR), MBFSZ (HU), VMM (BE)	
4. Monitoring wells with short screens (< 1m) with time series of pollutants and tracer estimated age distributions or mean travel times ?	GEUS(DK)	
5. time series for pollutants in water supply or monitoring wells with long screens, which have been age dated	BRGM (FR), GEUS (DK), EGT (EE), HGI-CGS (HR)	
6. water supply or monitoring wells with long screens where the groundwater age distribution have been estimated based on multiple tracers / groundwater age indicators ?	BRGM (FR), GEUS (DK), HGI-CGS (HR), MBFSZ (HU)	Other HOVER partners with such data: DE, NL & UK
7. water supply or monitoring wells with long screens for which groundwater age distributions have been estimated both by the application of multiple tracers and groundwater models ?	BRGM (FR), GEUS (DK), EGT (EE), HGI-CGS (HR), MBFSZ (HU)	
8. Do you have long screen wells, which clearly demonstrate bi- or even multimodal groundwater age distributions ?	GEUS(DK)	TNO (NL)
9. Have you identified Paleowaters (> 10.000 yrs) by tracers in any of your aquifers e.g. by age or recharge	BRGM(FR), GBA (AT), GEUS (DK), GSE (EE), IGR (RO), LGT (LT)	Please consult the groundwater map developed in

temperature (stable isotopes, heavy noble gases) indicators ?		RESOURCE WP6 for distribution of paleowaters in Europe. Other HOVER partner countires with such data include DE, NL and UK
10. Have you any water supply or other wells, which have been dated with combined use of 3H/3He, 85Kr and 39Ar ?	BRGM (FR), GSD (CY), GEUS (DK), EGT (EE), IGR (RO), SGU (SE)	
11. Are you using any kind of groundwater age grouping / classification such as "young, old, paleowaters" and in that case how are they defined ?	BRGM (FR), GSD (CY), GBA (AT), (GEUS (DK), (MBFSZ(HU)), (HGI-CGS (HR))	Approach vary between countries
12. Does pilot sites with existing groundwater age data or plans for groundwater age dating campaigns, which would be relevant for studies of groundwater age distributions in your country or in cross-border settings in HOVER WP6 exist? if so please name the suggested pilot sites	BRGM (FR), GEUS (DK) EGT (EE), SGU (SE)	Other HOVER partners with such plans: NL

*The table is not exhaustive but indicate the type of data and information available in each country.

APPENDIX B - TABLE OF MOST COMMON ENVIRONMENTAL TRACERS USED FOR ESTIMATION OF GROUNDWATER AGE DISTRIBUTIONS AND CORRECTIONS FOR GEOCHEMICAL REACTIONS

Tracer – isotopes and industrial gases (listed by increasing atomic / molecule weight)	**Unit**	**Stable or radioactive isotope**	**Half life**	**Applications of tracers**
Delta deute-rium	‰	Stable		Delta 2H may indicate lower recharge T and e.g. paleowaters
H-3[1]	TU	Radio-active	12.3	Measurable 3H indicate risk of pollution
He-3	Nml/Kg	Stable		For 3H/3He dating
Tritiogenic He-3	TU	Stable		For 3H/3He dating
He-4	Nml/Kg	stable		Sometimes used for relative or even absolute age dating if underground production can be estimated
Delta C-13	‰	stable		Used for correction of carbonate dissolution in 14C dating
C-14*	pmc	Radio-active	5730	Low 14C contents e.g. < 10 pmc (percent modern Carbon) indicate paleowater > 10.000 yr
delta O-18	‰	Stable		May indicate lower recharge T and e.g. paleowaters
Ar-37	mBq/ m^3air	Radio-active	0.0958	Support 39Ar interpretation
Ar-39*	pmAr	Radio-active	269	No or very low 39Ar indicate gw age > 1500 yr
Kr-81	pmKr	Radio-active	229000	81Kr is used for dating very old water/ice. Measured in percent of modern krypton. https://doi.org/10.1016/j.earscirev.2013.09.002
Kr-85*	dpm/cc	Radio-active	10.76	85Kr is used for dating of young groundwater (fraction)
CFC-12	ng/L	N/A	0	CFC-12 is used for dating of young groundwater (fraction)

CFC-11	ng/L	N/A	0	CFC-11 is used for dating of young groundwater (fraction)
CFC-113	ng/L	N/A	0	CFC-113 is used for dating of young groundwater (fraction)
SF6	fmol/l	N/A	0	Sulfur Hexafluoride is used for dating of young groundwater (fraction)
SF5CF3	fmol/l	N/A	0	Trifluoromethyl sulfur pentafluoride is used for dating of young groundwater (fraction)

[1] Highlighted radioactive isotopes that may also be named: 3H, 39Ar, 14C are the most important isotope tracers for estimation of groundwater age distributions within the age range of 1 – > 10.000 years. These tracers are of special interest for the assessment of the vulnerability of water supply wells towards pollution from the surface and assessment of the history and fate of contaminants in the subsurface. The industrial gases (CFCs and SF_6) may also be used for groundwater dating depending on the hydrogeological setting. Other tracers are helpful supporting parameters that may occasionally be applied for groundwater dating (4He) or indication of low recharge temperatures (delta O-18) or the heavy noble gases **. NOTE! Other environmental tracers than we list here may be uploaded as long as standard units and preferably analytical errors are provided**

APPENDIX C - TABLES OF ENVIRONMENTAL TRACERS, SUPPORTING PARAMETERS AND DERIVED /SIMULATED INFORMATION ON GROUNDWATER AGE DISTRIBUTIONS AND SUSCEPTIBILITY/VULNERABILITY ACCESSIBLE IN DATABASE

Table 1. Meta data and information to be stored with the age indicators and supporting parameters in table 2 and 3.

Sample ID	Sample no.	Well ID	INTAKE ID	Sampling date	Date of analysis	Sampling Temp.	Estimated recharge temp.	Elevation	Sample coordinates	Sample depth	USER ID

Table 2. Main groundwater age indicators / environmental tracers used for estimating groundwater age and travel time distributions

Tracer ID	Environmental Tracer (from appendix B	Conc. /activity	error	Analysis method	Sample ID (from table1)
	eg Kr-85				

Table 3. Simulated age distributions expressed as probability density functions (PDF), cumulative density functions (CDF) and derived parameters. The distributions may be computed e.g. by TracerLPM (TLPM), the DK-model or potentially other models derived parameters and susceptibility/vulnerability

Simulation ID	Model Type (from Model id table)	PDF ID	CDF	PDF plot[4]	CDF plot[4]	Mean or median? age[4]	Fraction of young water (recharged after 1950)[4]	Susceptibility Index[1] (SI)[4]	Simple Vulnerability class[2, 4]	SI-TLPM / SI-DK-model[3, 4]
	eg. TracerLPM									
	Eg. DK-model									
	Other									

[1]Solder et al. (2020), [2]E.g. 1 = vulnerable, 2=slightly vulnerable and 3= not vulnerable; [3]The ratio indicate the agreement between the two age distributions as simulated by TracerLPM / the DK-model. [4] Plottet on the fly

Table 4. Supporting simulation parameters needed for plotting of age distributions and TracerLPM simulations.

Simulation ID	Parameter	result
Eg DKM01	AP005	25.35
Eg.TrLPM01	LPM01	5.0

Table 5. Supporting parameters needed for model identification (might need more columns for general purpose, not only related to age simulation)

Model ID	Model Name	Model area	Model purpose	Model Type	Model Owner	Model Date	User ID	Note
				Eg. DK-model				
				TracerLPM				

Table 6. Supporting parameters needed for simulation identification (might need more columns for general purpose, not only related to age simulation).

Simulation ID	Model ID	Study area	Simulation purpose	Type	Report ID	Simulation Date	User ID	Note
				e.g. particle tracking				
				LPM				

Table 7. Supporting model parameters. AP001-AP100 are necessary parameters for production of CDF and PDF. The rest of the parameters are optional, but necessary if we want to facilitate and supportTracerLPM simulations

Parameter	PARM_NAME	SHORT_NAME	GROUP	NOTE	UNIT
AP001	Transport time for 1% percentile (>= 1% is younger than this age)	Age_percentile_001	Simulated age percentiles		YEAR
AP002	Transport time for 2% percentile (>= 2% is younger than this age)	Age_percentile_002	Simulated age percentiles		YEAR
…					
AP099	Transport time for 99% percentile (>= 99% is younger than this age)	Age_percentile_99	Simulated age percentiles		YEAR

AP100	Transport time for 100% percentile (>= 100% is younger than this age)	Age_percentile_100	Simulated age percentiles		YEAR
LPM01	UZ travel time	LPM_I_UZtt	Initial Model Values	5	YEAR
LPM02	Mean age	LPM_I_Age_C1	Initial Model Values	6	YEAR
LPM03	Model Parameter 1	LPM_I_ModParm1_C1	Initial Model Values	7	
LPM04	Model Parameter 2	LPM_I_ModParm2_C1	Initial Model Values	8	
LPM05	Fraction	LPM_I_Fraction_C1	Initial Model Values	9	
LPM06	2nd Mean age, years	LPM_I_Age_C2	Initial Model Values	10	
LPM07	2nd Model Parameter 1	LPM_I_ModParm1_C2	Initial Model Values	11	
LPM08	2nd Model Parameter 2	LPM_I_ModParm2_C2	Initial Model Values	12	
LPM09	Optimizatio n Type	LPM_TypeOfOpt	Lumped Parameter Modeling Results	13	

LPM10	LPM name	LPM_Name	Lumped Parameter Modeling Results	14	
LPM11	Free Model Parameters	LPM_Parms	Lumped Parameter Modeling Results	15	
LPM12	Chi-Square (sum of weighted squared residuals)	LPM_ChiSqr	Lumped Parameter Modeling Results	16	
LPM13	Chi-Square Probability	LPM_Prob	Lumped Parameter Modeling Results	17	
LPM14	UZ travel time, years	LPM_UZtt_yrs	Lumped Parameter Modeling Results	18	
LPM15	UZ travel time error, years	LPM_UZtt_Err_yrs	Lumped Parameter Modeling Results	19	
LPM16	Mean age, years	LPM_Age_C1_yrs	Lumped Parameter Modeling Results	20	
LPM17	Mean age error, years	LPM_Age_Err_C1_yrs	Lumped Parameter Modeling Results	21	

LPM18	Model Parameter 1	LPM_ModParm1_C1	Lumped Parameter Modeling Results	22	
LPM19	Model Parameter 1 error	LPM_ModParm1_C1_Err	Lumped Parameter Modeling Results	23	
LPM20	Model Parameter 2	LPM_ModParm2_C1	Lumped Parameter Modeling Results	24	
LPM21	Model Parameter 2 error	LPM_ModParm2_C1_Err	Lumped Parameter Modeling Results	25	
LPM22	Fraction	LPM_Fraction_C1	Lumped Parameter Modeling Results	26	
LPM23	Fraction error	LPM_Fraction_C1_Err	Lumped Parameter Modeling Results	27	
LPM24	Mean age (component 2), years	LPM_Age_C2	Lumped Parameter Modeling Results	28	
LPM25	Mean age error (component 2), years	LPM_Age_C2_Err	Lumped Parameter Modeling Results	29	

LPM26	Model Parameter 1 (component 2)	LPM_ModParm1_C2	Lumped Parameter Modeling Results	30	
LPM27	Model Parameter 1 error (component 2)	LPM_ModParm1_C2_Err	Lumped Parameter Modeling Results	31	
LPM28	Model Parameter 2 (component 2)	LPM_ModParm2_C2	Lumped Parameter Modeling Results	32	
LPM29	Model Parameter 2 error (component 2)	LPM_ModParm2_C2_Err	Lumped Parameter Modeling Results	33	
LPM30	Tracers Modeled	LPM_TracersMod	Lumped Parameter Modeling Results	34	
LPM31	HiTracer	LPM_HiTracer	Lumped Parameter Modeling Results	35	
LPM32	Hi Tracer Chi-Sqr	LPM_HiTracerChiSqr	Lumped Parameter Modeling Results	36	
LPM33	Number of iterations	LPM_NumOfIters	Lumped Parameter Modeling Results	37	

LPM34	Model solution time, seconds	LPM_ModSolnTime	Lumped Parameter Modeling Results	38	
LPM35	Model date stamp	LPM_ModelDate	Lumped Parameter Modeling Results	39	
LPM40	Tracer 1, model conc.	LPM_Mod_Tracer_01	Lumped Parameter Model Concentrations	40	
LPM41	Tracer 2, model conc.	LPM_Mod_Tracer_02	Lumped Parameter Model Concentrations	41	
LPM42	Tracer 3, model conc.	LPM_Mod_Tracer_03	Lumped Parameter Model Concentrations	42	
LPM43	Tracer 4, model conc.	LPM_Mod_Tracer_04	Lumped Parameter Model Concentrations	43	
LPM44	Tracer 5, model conc.	LPM_Mod_Tracer_05	Lumped Parameter Model Concentrations	44	
LPM45	Tracer 6, model conc.	LPM_Mod_Tracer_06	Lumped Parameter Model Concentrations	45	

LPM46	Tracer 7, model conc.	LPM_Mod_Tracer_07	Lumped Parameter Model Concentrations	46	
LPM47	Tracer 8, model conc.	LPM_Mod_Tracer_08	Lumped Parameter Model Concentrations	47	
LPM48	Tracer 9, model conc.	LPM_Mod_Tracer_09	Lumped Parameter Model Concentrations	48	
LPM49	Tracer 10, model conc.	LPM_Mod_Tracer_10	Lumped Parameter Model Concentrations	49	
LPM50	Comments	Comments	Reported Results	180	
LPM51	Total mean age	TotAge_yrs	Reported Results	156	YEAR
LPM52	Total mean age error	TotAge_Err_yrs	Reported Results	157	YEAR
LPM53	Reported Total mean age	Rpt_TotAge_yrs	Reported Results	158	YEAR
LPM54	Reported Total mean age error	Rept_TotAge_Err_yrs	Reported Results	159	YEAR
LPM55	Reported fraction modern	Rpt_FracModern	Reported Results	160	
LPM56	Reported Susceptibility index	Rpt_SuscIndex	Reported Results	161	
LPM57	Reported Chi-Square	Rpt_ChiSquare	Reported Results	162	

LPM58	Reported Probability	Rpt_Probability	Reported Results	163	
LPM59	Reported UZ travel time	Rpt_UZtt_yrs	Reported Results	164	YEAR
LPM60	Reported UZ travel time error	Rpt_UZtt_Err_yrs	Reported Results	165	YEAR
LPM61	Reported Mean age	Rpt_Age_C1_yrs	Reported Results	166	YEAR
LPM62	Reported Mean age error	Rpt_Age_Err_C1_yrs	Reported Results	167	YEAR
LPM63	Reported Model Parameter 1	Rpt_ModParm1_C1	Reported Results	168	
LPM64	Reported Model Parameter 1 error	Rpt_ModParm1_C1_Err	Reported Results	169	
LPM65	Reported Model Parameter 2	Rpt_ModParm2_C1	Reported Results	170	
LPM66	Reported Model Parameter 2 error	Rpt_ModParm2_C1_Err	Reported Results	171	
LPM67	Reported Fraction	Rpt_Fraction_C1	Reported Results	172	
LPM68	Reported Fraction error	Rpt_Fraction_C1_Err	Reported Results	173	
LPM69	Reported Mean age (component 2)	Rpt_Age_C2	Reported Results	174	YEAR
LPM70	Reported Mean age error (component 2)	Rpt_Age_C2_Err	Reported Results	175	YEAR
LPM71	Reported Model Parameter 1	Rpt_ModParm1_C2	Reported Results	176	

	(component 2)				
LPM72	Reported Model Parameter 1 error (component 2)	Rpt_ModParm1_C2_Err	Reported Results	177	
LPM73	Reported Model Parameter 2 (component 2)	Rpt_ModParm2_C2	Reported Results	178	
LPM74	Reported Model Parameter 2 error (component 2)	Rpt_ModParm2_C2_Err	Reported Results	179	
MCS01	Num. of Monte Carlo sims	LPM_MC_NumOfSims	Monte Carlo Results	70	
MCS02	Simulation time, seconds	LPM_MC_ModSimTime	Monte Carlo Results	71	
MCS03	UZ travel time	LPM_MC_UZtt_yrs	Monte Carlo Results	72	YEAR
MCS04	UZ travel time error	LPM_MC_UZtt_Err_yrs	Monte Carlo Results	73	YEAR
MCS05	Mean age	LPM_MC_Age_C1_yrs	Monte Carlo Results	74	YEAR
MCS06	Mean age error	LPM_MC_Age_Err_C1_yrs	Monte Carlo Results	75	YEAR
MCS07	Model Parameter 1	LPM_MC_ModParm1_C1	Monte Carlo Results	76	

MCS08	Model Parameter 1 error	LPM_MC_ModParm1_C1_Err	Monte Carlo Results	77	
MCS09	Model Parameter 2	LPM_MC_ModParm2_C1	Monte Carlo Results	78	
MCS10	Model Parameter 2 error	LPM_MC_ModParm2_C1_Err	Monte Carlo Results	79	
MCS11	Fraction	LPM_MC_Fraction_C1	Monte Carlo Results	80	
MCS12	Fraction error	LPM_MC_Fraction_C1_Err	Monte Carlo Results	81	
MCS13	Mean age (component 2)	LPM_MC_Age_C2	Monte Carlo Results	82	YEAR
MCS14	Mean age error (component 2)	LPM_MC_Age_C2_Err	Monte Carlo Results	83	YEAR
MCS15	Model Parameter 1 (component 2)	LPM_MC_ModParm1_C2	Monte Carlo Results	84	
MCS16	Model Parameter 1 error (component 2)	LPM_MC_ModParm1_C2_Err	Monte Carlo Results	85	
MCS17	Model Parameter 2 (component 2)	LPM_MC_ModParm2_C2	Monte Carlo Results	86	
MCS18	Model Parameter 2 error (component 2)	LPM_MC_ModParm2_C2_Err	Monte Carlo Results	87	

MCS19	Tracer 1, empty	LPM_MC_Sim_Tracer_01	Monte Carlo Tracer Results	88	
MCS20	Tracer 1, std. err.	LPM_MC_Sim_Tracer_01_Err	Monte Carlo Tracer Results	89	
MCS21	Tracer 2, empty	LPM_MC_Sim_Tracer_02	Monte Carlo Tracer Results	90	
MCS22	Tracer 2, std. err.	LPM_MC_Sim_Tracer_02_Err	Monte Carlo Tracer Results	91	
MCS23	Tracer 3, empty	LPM_MC_Sim_Tracer_03	Monte Carlo Tracer Results	92	
MCS24	Tracer 3, std. err.	LPM_MC_Sim_Tracer_03_Err	Monte Carlo Tracer Results	93	
MCS25	Tracer 4, empty	LPM_MC_Sim_Tracer_04	Monte Carlo Tracer Results	94	
MCS26	Tracer 4, std. err.	LPM_MC_Sim_Tracer_04_Err	Monte Carlo Tracer Results	95	
MCS27	Tracer 5, empty	LPM_MC_Sim_Tracer_05	Monte Carlo Tracer Results	96	
MCS28	Tracer 5, std. err.	LPM_MC_Sim_Tracer_05_Err	Monte Carlo Tracer Results	97	

MCS29	Tracer 6, empty	LPM_MC_Sim_Tracer_06	Monte Carlo Tracer Results	98	
MCS30	Tracer 6, std. err.	LPM_MC_Sim_Tracer_06_Err	Monte Carlo Tracer Results	99	
MCS31	Tracer 7, empty	LPM_MC_Sim_Tracer_07	Monte Carlo Tracer Results	100	
MCS32	Tracer 7, std. err.	LPM_MC_Sim_Tracer_07_Err	Monte Carlo Tracer Results	101	
MCS33	Tracer 8, empty	LPM_MC_Sim_Tracer_08	Monte Carlo Tracer Results	102	
MCS34	Tracer 8, std. err.	LPM_MC_Sim_Tracer_08_Err	Monte Carlo Tracer Results	103	
MCS35	Tracer 9, empty	LPM_MC_Sim_Tracer_09	Monte Carlo Tracer Results	104	
MCS36	Tracer 9, std. err.	LPM_MC_Sim_Tracer_09_Err	Monte Carlo Tracer Results	105	
MCS37	Tracer 10, empty	LPM_MC_Sim_Tracer_10	Monte Carlo Tracer Results	106	
MCS38	Tracer 10, std. err.	LPM_MC_Sim_Tracer_10_Err	Monte Carlo Tracer Results	107	

TIV01	Tracer Name 1	LPM_Tracer_Name_01	Tracer Input Variables	108	
TIV02	Tracer Name 2	LPM_Tracer_Name_02	Tracer Input Variables	109	
TIV03	Tracer Name 3	LPM_Tracer_Name_03	Tracer Input Variables	110	
TIV04	Tracer Name 4	LPM_Tracer_Name_04	Tracer Input Variables	111	
TIV05	Tracer Name 5	LPM_Tracer_Name_05	Tracer Input Variables	112	
TIV06	Tracer Name 6	LPM_Tracer_Name_06	Tracer Input Variables	113	
TIV07	Tracer Name 7	LPM_Tracer_Name_07	Tracer Input Variables	114	
TIV08	Tracer Name 8	LPM_Tracer_Name_09	Tracer Input Variables	115	
TIV09	Tracer Name 9	LPM_Tracer_Name_09	Tracer Input Variables	116	
TIV10	Tracer Name 10	LPM_Tracer_Name_10	Tracer Input Variables	117	

TIV11	Tracer Input Source 1	LPM_TracerInput_01	Tracer Input Variables	118	
TIV12	Tracer Input Source 2	LPM_TracerInput_02	Tracer Input Variables	119	
TIV13	Tracer Input Source 3	LPM_TracerInput_03	Tracer Input Variables	120	
TIV14	Tracer Input Source 4	LPM_TracerInput_04	Tracer Input Variables	121	
TIV15	Tracer Input Source 5	LPM_TracerInput_05	Tracer Input Variables	122	
TIV16	Tracer Input Source 6	LPM_TracerInput_06	Tracer Input Variables	123	
TIV17	Tracer Input Source 7	LPM_TracerInput_07	Tracer Input Variables	124	
TIV18	Tracer Input Source 8	LPM_TracerInput_08	Tracer Input Variables	125	
TIV19	Tracer Input Source 9	LPM_TracerInput_09	Tracer Input Variables	126	
TIV20	Tracer Input Source 10	LPM_TracerInput_10	Tracer Input Variables	127	

TIV21	Scaling Factor 1	LPM_ScaleFact_01	Tracer Input Variables	128	
TIV22	Scaling Factor 2	LPM_ScaleFact_02	Tracer Input Variables	129	
TIV23	Scaling Factor 3	LPM_ScaleFact_03	Tracer Input Variables	130	
TIV24	Scaling Factor 4	LPM_ScaleFact_04	Tracer Input Variables	131	
TIV25	Scaling Factor 5	LPM_ScaleFact_05	Tracer Input Variables	132	
TIV26	Scaling Factor 6	LPM_ScaleFact_06	Tracer Input Variables	133	
TIV27	Scaling Factor 7	LPM_ScaleFact_07	Tracer Input Variables	134	
TIV28	Scaling Factor 8	LPM_ScaleFact_08	Tracer Input Variables	135	
TIV29	Scaling Factor 9	LPM_ScaleFact_09	Tracer Input Variables	136	
TIV30	Scaling Factor 10	LPM_ScaleFact_10	Tracer Input Variables	137	

TIV31	UZ travel time treatment 1	LPM_UZtt_Treat_01	Tracer Input Variables	138	
TIV32	UZ travel time treatment 2	LPM_UZtt_Treat_02	Tracer Input Variables	139	
TIV33	UZ travel time treatment 3	LPM_UZtt_Treat_03	Tracer Input Variables	140	
TIV34	UZ travel time treatment 4	LPM_UZtt_Treat_04	Tracer Input Variables	141	
TIV35	UZ travel time treatment 5	LPM_UZtt_Treat_05	Tracer Input Variables	142	
TIV36	UZ travel time treatment 6	LPM_UZtt_Treat_06	Tracer Input Variables	143	
TIV37	UZ travel time treatment 7	LPM_UZtt_Treat_07	Tracer Input Variables	144	
TIV38	UZ travel time treatment 8	LPM_UZtt_Treat_08	Tracer Input Variables	145	
TIV39	UZ travel time treatment 9	LPM_UZtt_Treat_09	Tracer Input Variables	146	
TIV40	UZ travel time treatment 10	LPM_UZtt_Treat_10	Tracer Input Variables	147	

TIV41	Dissolved inorganic carbon 1	LPM_DIC_C1	Tracer Input Variables	148	
TIV42	Dissolved inorganic carbon 2	LPM_DIC_C2	Tracer Input Variables	149	
TIV43	Uranium	LPM_U_ppm	Tracer Input Variables	150	PPM
TIV44	Thorium	LPM_Th_ppm	Tracer Input Variables	151	PPM
TIV45	Porosity	LPM_Porosity	Tracer Input Variables	152	
TIV46	Bulk Density	LPM_BulkDensity	Tracer Input Variables	153	
TIV47	Helium solution rate	LPM_He_SolnRate_ccpgpyr	Tracer Input Variables	154	
TIV48	Time Increment	LPM_TimeStepOfInput	Tracer Input Variables	155	
TRC01	Tracer 1	LPM_Meas_Tracer_01	Measured Tracer Data	50	TracerID from table 2.. TracerLPM needs parameters for sample

					conc. & std err.
TRC03	Tracer 2	LPM_Meas_Tracer_02	Measured Tracer Data	52	TracerID from table 2.. TracerLPM needs parameters for sample conc. & std err.
TRC05	Tracer 3	LPM_Meas_Tracer_03	Measured Tracer Data	54	TracerID from table 2.. TracerLPM needs parameters for sample conc. & std err.
TRC07	Tracer 4	LPM_Meas_Tracer_04	Measured Tracer Data	56	TracerID from table 2.. TracerLPM needs parameters for sample conc. & std err.
TRC09	Tracer 5	LPM_Meas_Tracer_05	Measured Tracer Data	58	TracerID from table 2.. TracerLPM needs parameters for sample conc. & std err.

TRC11	Tracer 6	LPM_Meas_Tracer_06	Measured Tracer Data	60	TracerID from table 2.. TracerLPM needs parameters for sample conc. & std err.
TRC13	Tracer 7	LPM_Meas_Tracer_07	Measured Tracer Data	62	TracerID from table 2.. TracerLPM needs parameters for sample conc. & std err.
TRC15	Tracer 8	LPM_Meas_Tracer_08	Measured Tracer Data	64	TracerID from table 2.. TracerLPM needs parameters for sample conc. & std err.
TRC17	Tracer 9	LPM_Meas_Tracer_09	Measured Tracer Data	66	TracerID from table 2.. TracerLPM needs parameters for sample conc. & std err.
TRC19	Tracer 10	LPM_Meas_Tracer_10	Measured Tracer Data	68	TracerID from table 2.. TracerLPM needs

					parameters for sample conc. & std err.