REPORT

Multi-scale characterization of a complex karst and alluvial aquifer system in southern Germany using a combination of different tracer methods

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Abstract

Water suppliers face major challenges such as climate change and population growth. To prepare for the future, detailed knowledge of water resources is needed. In southern Germany, the state water supplier Zweckverband Landeswasserversorgung provides 3 million people with drinking water obtained from a complex karst and alluvial aquifer system and the river Danube. In this study, a combination of different tracing techniques was used with the goal of a multi-scale characterization of the aquifer system and to gain additional knowledge about groundwater flow toward the extraction wells in the Danube Valley. For the small-scale characterization, selected groundwater monitoring wells were examined using single-borehole dilution tests. With these tests, a wide range of flow behavior could be documented, including fast outflow within just a few hours in wells with good connection to the aquifer, but also durations of many weeks in low-permeability formations. Vertical flow, caused by multiple flow horizons or uprising groundwater, was detected in 40% of the tested wells. A regional multi-tracer test with three injections was used to investigate the aquifer on a large scale. For the highly karstified connection between a swallow hole and a spring group, high flow velocities of around 80 m/h could be documented. Exceptionally delayed arrivals, 250 and 307 days after the injection, respectively showing maximum velocities of 0.44 and 0.39 m/h, were observed in an area where low-permeability sediments overlay the karst conduits. With the chosen methods, a distinct heterogeneity caused by the geological setting could be documented on both scales.

Keywords Karst · Tracer test · Germany · Water supply · Groundwater flow

Introduction

Providing high-quality drinking water is one of the major challenges of increasing severity that every country or region in the world has to face. In particular, these challenges include the effects of climate change, such as the increasing severity and number of extreme weather events like droughts and heavy rain events, and the growing population, leading to growing stress on the global water supply (Bates et al. 2008; Delpla et al. 2009; Hanjra and Qureshi 2010; Wheeler and von Braun 2013; Olmstead 2014; Stevanović 2019). Apart from supplying the population with drinking

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and process water, the availability of a substantial amount of water is also crucial for the prosperity and economic development of a region (Olmstead 2014; World Bank 2016).

In southern Germany, water availability is generally sufficient; however, especially at the beginning of the twentieth century, water supply was problematic in some regions, e.g. the Swabian Alb. This historically and culturally important karst landscape (Goldscheider 2019), which is also a UNESCO Global Geopark, is characterized by a distinct karstification of the Jurassic limestones, leading to a lack of surface waters. Also, since the groundwater level is deep below the surface, inhabitants of the Swabian Alb mostly had to rely on dammed ponds with poor quality as their water source (Zweckverband Landeswasserversorgung 2012).

Also in the middle Neckar region, water supply has been critical due to problems with water availability and quality, caused by an enormous population increase and fecal contamination. In the course of industrialization, the population in Stuttgart grew from 119,000 to 253,000 between 1882

and 1907, and the supply of water could barely keep up with the demand. The development of new water resources was inevitable, especially considering that the region is a center of commerce and industry (Zweckverband Landeswasserversorgung 2012). Ideas to provide Stuttgart with water from Lake Constance, the northern Black Forest, or the Neckar Valley were discarded. Finally, the Danube Valley was chosen due to its high quality and rich groundwater resources, fed by inflow from the large Jurassic karst aquifer of the eastern Swabian Alb. Finally, the state water supplier Zweckverband Landeswasserversorgung (LW) was founded in 1912 and a long-distance water supply system for Stuttgart and the eastern Swabian Alb was established. Gradually, more cities and communities joined the association, so that today the economically important triangle, between Stuttgart, Ulm and Aalen, is supplied by this state water supplier (Zweckverband Landeswasserversorgung 2012).

Nowadays, high-quality drinking water for approximately 3 million people in Baden-Wuerttemberg is provided with a maximum capacity of 5,200 L/s. Most of the water is gained through more than 200 extraction wells in the Danube Valley, with a total maximum extraction rate of 2,500 L/s. Additionally, the state water supplier extracts water from the river Danube, on average 1,100 L/s, and the captured Buchbrunnen spring, with up to 800 L/s. For periods of peak demand, deep karst extraction wells near the village of Burgberg can be used to provide an extra 500 L/s. In recent years, the average amount of distributed water is around 100 MCM/a (million cubic meters per year, Zweckverband Landeswasserversorgung 2021). Approximately 50% of this water is obtained from groundwater originating in the karst aquifer, making the state water supplier Zweckverband Landeswasserversorgung comparable to the largest karst water supplier in Europe, the Vienna water supplier, which uses multiple karst springs to provide water for 1.7 million citizens (Stevanović 2019).

Currently, Zweckverband Landeswasserversorgung is facing challenges such as climate change, extreme weather events (Haakh 2019), and increasing nitrate concentrations caused by intense agriculture within the groundwater protection area (Haakh 2018). To address and prepare for these tasks, a better knowledge of the catchment area, which extends over the eastern Swabian Alb and parts of the Danube Valley, is required. A project was launched with the aim of a multi-scale characterization of the complex aquifer system and the flow toward the extraction wells. Due to the distinct heterogeneity of karst, it is very difficult to characterize and represent a karst system in detail with numerical models alone. Here, a combination of tracing techniques on different scales was chosen to identify processes in the catchment, beginning with the western part.

The main objectives of this study were (1) to examine groundwater flow on a small scale by conducting single-borehole dilution tests (SBDT) in groundwater monitoring wells (GMW) focusing on identification of flow horizons, outflow behavior and potential vertical flow, (2) to evaluate selected GMWs with SBDT with regard to their suitability as injection points for a large-scale tracer test, (3) to identify hydraulic connections, flow velocities, and subcatchments on a regional scale with a multi-tracer test, focusing on groundwater flow from areas with potential contamination risk towards the extraction wells in the Danube Valley, and (4) to evaluate the obtained results of the regional tracer tests with regard to inflow to the extraction wells and the existing protection concept. The overall goal of this study is to add to the existing knowledge about the aquifer system and groundwater flow on small- and regional scale, in order to prepare for future challenges.

Materials and methods

Study site

Groundwater protection area Donauried-Hürbe

The groundwater protection area of the state water supply, at more than 510 km^2, is one of the largest in Germany. It is located in eastern Baden-Wuerttemberg and was established for the extraction wells in the Danube Valley. A total of 204 wells, subdivided into six well fields, extract water either from the Quaternary alluvial aquifer, which is fed by the Jurassic karst aquifer, or directly from the karst aquifer. Each well field has its own pumping station that pumps the extracted water towards the waterworks. The recharge area of the extraction wells is not perfectly represented by the groundwater protection area, since the European watershed (Fig. 1) crosses the area in the northwest (Schloz et al. 2007). The ground elevation drops from about 700 m asl in the area of the watershed to 450 m asl in the Danube Valley.

Geology

From a geological point of view, the water protection area can be divided into two sectors: the Swabian Alb, which is composed of Jurassic limestones and marls, and the alluvial plain of the Danube Valley (Donauried), where the limestones are overlain by Oligocene, Miocene, and Quaternary sediments (Schloz et al. 2007).

The Jurassic formations in the Swabian Alb have thicknesses of up to 400 m and dip gently toward the southeast. In the study area, bedded facies and reef limestones occur, with the latter showing the strongest karstification (Schloz et al. 2007). In the northwestern part of the groundwater monitoring area, Oligocene and Miocene molasse deposits on top of the limestones are few or entirely absent. Toward
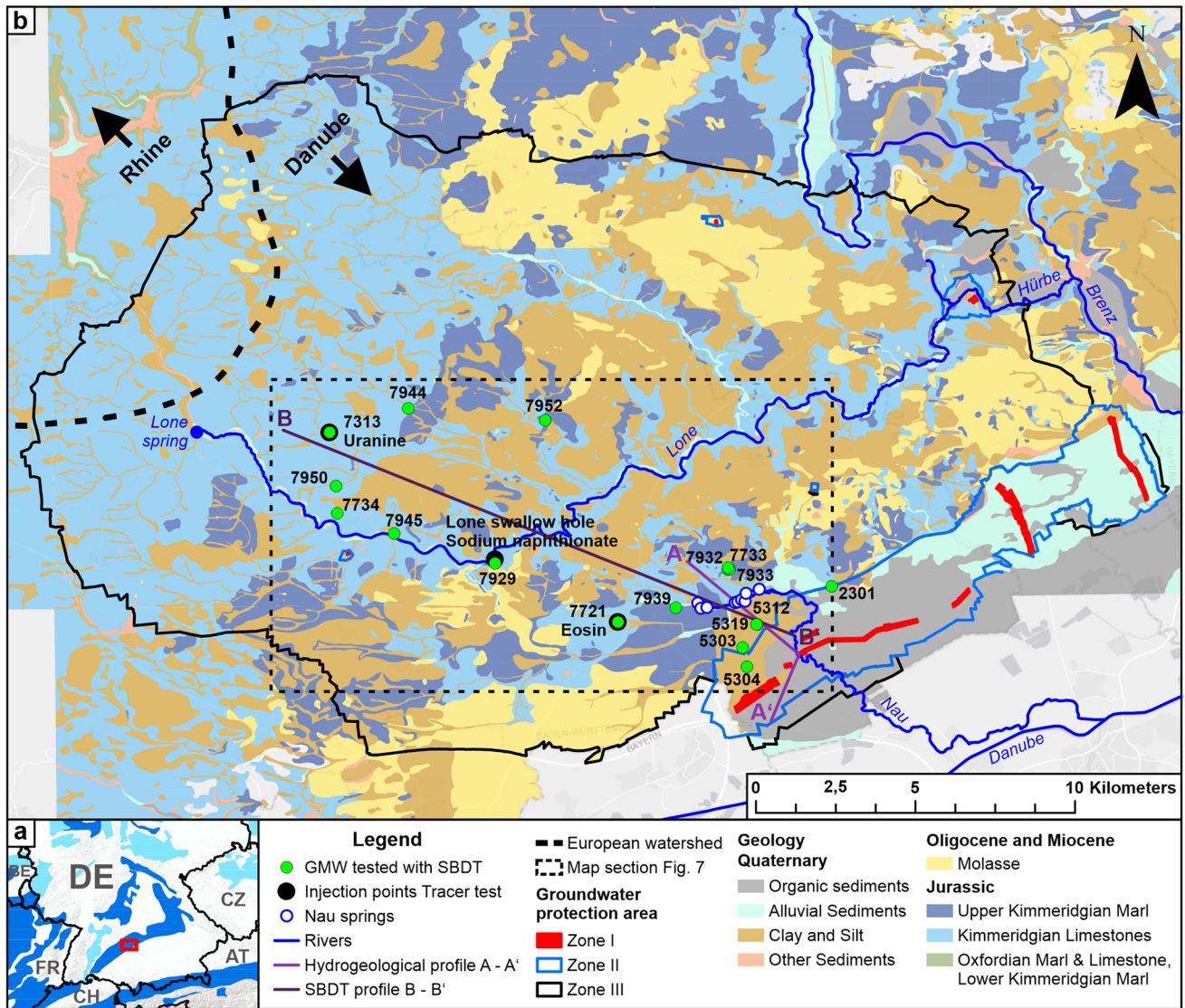
Fig. 1 a Location of the study site (red box) shown on a portion of the World Karst Aquifer Map (WOKAM, Chen et al. 2017. Dark blue: continuous carbonate rocks; light blue: discontinuous carbonate rocks; country codes from ISO.org 2021). b Geological map of the groundwater protection area of the state water supplier Zweckverband Landeswasserversorgung, with locations of groundwater monitoring wells (GMW) tested with single-borehole dilution tests (SBDT)

the southeast, the molasse covering increases with increasing thickness. In the area of the Danube Valley, the limestones are covered almost entirely, with thicknesses up to 90 m (Schloz et al. 2007). In the Danube Valley, the molasse is overlain by Quaternary gravels and sands with thicknesses of up to 11 m. The youngest units are mostly redistributed deposits and river sediments covered by clay, silt, peat or other organic sediments (Udluft et al. 2000; Schloz et al. 2007).

Hydrogeology

The limestones form a large-volume karst aquifer that is underlain by the low-permeability lower Kimmeridgian

marls, which form the base of the karst in the catchment (Fig. 2). The tracer tests in the adjacent areas demonstrate a high degree of heterogeneity with flow velocities of more than 100 m/h, indicating highly karstified zones, mainly toward springs, but low velocities and long travel times in zones with low permeabilities (Kolokotronis et al. 2002). Groundwater recharge is mainly attributed to diffuse percolation of precipitation through shallow soils and epikarst, or small watercourses sinking into swallow holes; the water then flows towards the southeast (Kolokotronis et al. 2002). A large quantity of the karst groundwater transits into the alluvial aquifer, consisting of the Quaternary gravels and sands in the Daube Valley, in zones where the

Fig. 2 Hydrogeological profile A–A′. Due to eroded molasse at the border between Swabian Alb and Danube Valley, karst groundwater can flow directly into the alluvial aquifer
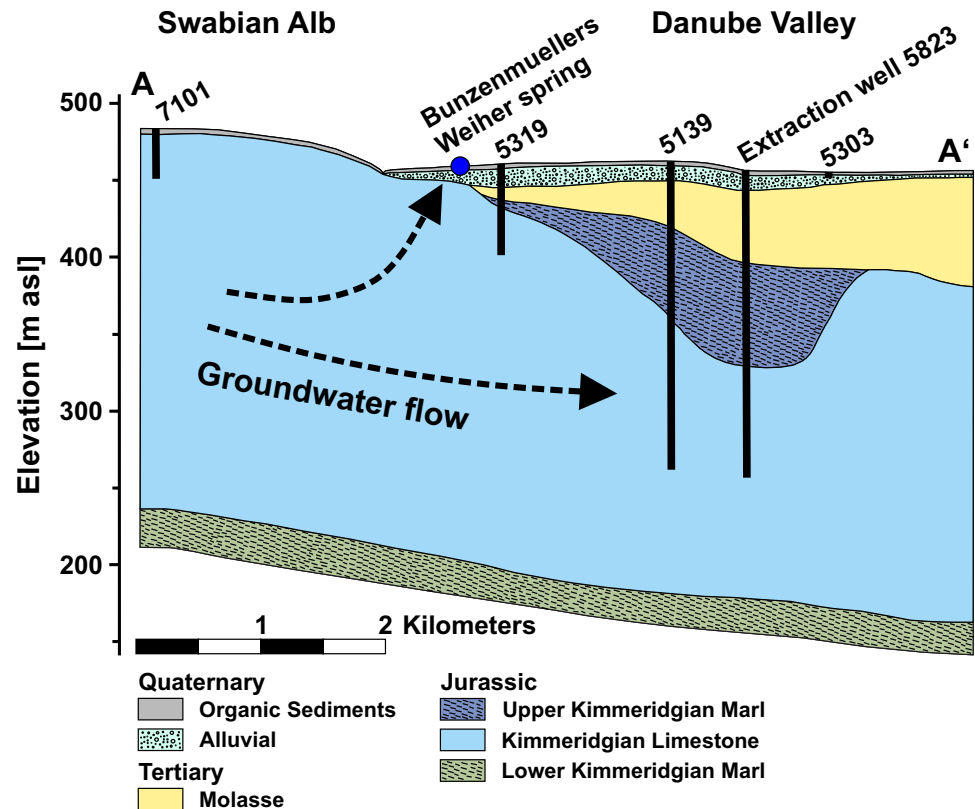
low-permeability molasse sediments ($k = 10^{-6} - 10^{-5}$ m/s) were eroded, e.g. in the northern part of the Danube Valley where the gravels lie directly on top of the Jurassic limestones, or show just minor thicknesses. Additionally, karst groundwater can rise into the alluvial aquifer through fractures in the molasse layer (Kolokotronis et al. 2002). Zones with ascending karst groundwater can be localized via temperature anomalies or chemical analyses (Udluft et al. 2000).

In the northwestern part of the groundwater protection area, there is only one large spring, the Lone spring, which discharges 240 L/s on average but up to 3,200 L/s during high-flow conditions (Schloz et al. 2007). Based on age dating with tritium, the water of the Lone spring shows an average residence time of 22 years (Kolokotronis et al. 2002). The spring feeds the Lone River, whose valley crosses the catchment area from west to east. However, due to several swallow holes, most of the river bed is dry; water reaches the Hürbe River only after strong rainfall or during snowmelt. Only a few kilometers beyond the Lone spring and the segments beyond the inflow from the wastewater treatment plants are continuously water-bearing.

The Nau springs, the most important springs in the catchment, are located in the town of Langenau at the border between the Swabian Alb and Danube Valley. A large number of sources, summarized as eight spring groups distributed along the west–east axis through the town, partially discharge the karst groundwater flowing toward the southeast. Discharges of the individual spring groups vary between 5 and more than 200 L/s, and the total accounts for an average of 1,230 L/s (Schloz et al. 2007). The westernmost spring group, Nauursprung spring, was also dated using tritium. This dating investigation showed a mean residence time of 47 years (Kolokotronis et al. 2002), but it did not include any information on the fast-flowing components toward the spring.

In the area surrounding the catchment, numerous tracer tests have been conducted in the past. Yet only one large-scale test with an observed breakthrough was performed investigating the inflow of the Nau springs and the extraction wells in the Danube Valley. A total of 25 kg of uranine was injected in an active swallow hole southwest of Gerstetten on 2 December 1969 and detected at Nauursprung spring. According to Kolokotronis et al. (2002), two values for the maximum velocity can be found, 352 and 823 m/h. Since comparable tests in the surrounding area show maxima between 23 and 167 m/h, Kolokotronis et al. (2002) assess the obtained velocities as questionable.

Single-borehole dilution test methods

Single-borehole dilution test methods are based on the injection of tracer, e.g. fluorescence dyes, NaCl, or heated

Fig. 3 **a** Results of the point injection in GMW 7950 on 20 April 2021 show a fast upward movement of the tracer plume. **b** Normalized concentration profiles of a uniform injection in GMW 7945, with the major flow horizon at a depth of 36 m. **c** Normalized concentration profiles of a uniform injection in GMW 7929, which shows a significantly slower outflow
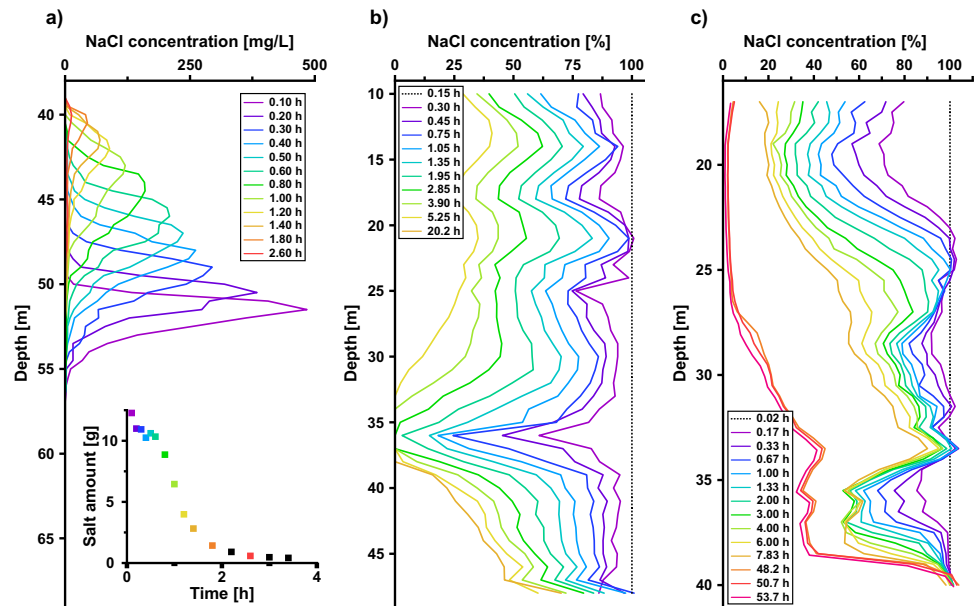
water, in the saturated zone of a borehole or well, followed by the observation of outflow with measurements of multiple concentration profiles (Brouyère et al. 2008; Maurice et al. 2011; Banks et al. 2014; Libby and Robbins 2014; Read et al. 2014; Poulsen et al. 2019; Fahrmeier et al. 2021). SBDTs can be conducted as uniform injections over the entire saturated length, delivering results for the whole well or borehole. For detailed information of one specific depth or the investigation of vertical flow, point injections can be used (Maurice et al. 2011).

Most uniform injections were performed using fine-grained NaCl and a permeable injection bag (PIB) to achieve a homogeneous tracer concentration in the well (Fahrmeier et al. 2021). Others were conducted using the hosepipe method, which involves lowering a hosepipe into the well, filling it with tracer solution, and then pulling it out with a constant speed to obtain a uniform injection (West and Odling 2007; Maurice et al. 2011). Point injections were conducted with a newly developed injection probe that contains tracer solution and is opened by dropping a weight down the line (Fahrmeier et al. 2022). After all injections, multiple profiles of the electrical conductivity were measured in time intervals that were chosen depending on the recorded changes. The method by which the data were further analyzed is described in Fahrmeier et al. (2021).

Between 2016 and 2021, 17 different GMWs in the groundwater protection area were tested using SBDTs. Thirteen of them are karst GMWs covering depth ranges between 9 and 122 m, with the longest saturated length being 51 m. The other four are alluvial GMWs located in the Danube Valley with depths up to 16 m. A total of 51 SBDTs were conducted, 41 of which were uniform injections (28 in karst wells, 13 in alluvial wells), mostly conducted with the PIB method. The other 10 were point injections in karst wells (3) and alluvial wells (7).

Goals of the SBDTs were to identify possible injection points for the regional tracer, to determine groundwater flow through and within monitoring wells, to evaluate the connections to the aquifer, and to detect in- and outflow horizons, as well as vertical flow. Also, with results from multiple wells, the objective was to develop an overall hydraulic characterization of the aquifer and its flow conditions.

Regional multi-tracer test

Within the scope of this study, possible tracer injection points, swallow holes and GMWs were identified within the catchment area. To test the GMW connections to the aquifer, uniform SBDTs were conducted in selected wells. Besides the flow conditions, the proximity to areas or industry with an increased contamination risk was taken into account. For the multi-tracer test, three injection points representing the western inflow were chosen (Fig. 1).

In all, 16 kg of uranine was injected into GMW 7313 on 11 October 2017. This site was chosen due to its large distance to the extraction wells, with the goal to characterize flow from distant parts of the catchment area. Two SBDTs conducted in the well before the tracer test showed an outflow zone between the water level (60–65 m depth) and a depth of 70 m (all depths refer to the respective well cap); below this zone the well showed just minor outflow. To cut off the inactive part of the well, a hydraulic packer was installed at a depth of 70 m before injecting the uranine using a hosepipe. After removing the packer 2 weeks later,

a measurement of a concentration profile with a borehole field fluorometer showed only minimal uranine concentrations below 70 m, indicating that the packer had functioned correctly.

Also on 11 October 2017, 95 kg of sodium naphthionate was injected in the Lone swallow hole north of the village Bernstadt. Just 500 m upstream of the swallow hole, a wastewater treatment plant discharges its water into the Lone, which poses a potential risk. In the event of a technical problem in the treatment process, contaminants can be transported into the aquifer within less than 1 h. Due to several beaver dams, the swallow hole was not active, but in consultation with the local authorities, the dams were opened slightly, resulting in a steady infiltration for several hours.

On 12 October 2017, 14 kg of eosin was injected in GMW 7721. This particular GMW was chosen due to its location close to a hazardous materials storage unit and an old landfill site. Also, with a saturated length of approximately 50 m, it covers a large depth range and shows a fast outflow over the entire length. For this reason, the tracer was distributed throughout the well by moving the hosepipe up and down during the injection.

A total of 72 sampling points, including springs, surface water, pumping stations, extraction wells, alluvial GMWs and karst GMWs, were monitored using water samples (taken manually and automated), activated charcoal adapters, and field fluorometers. Especially due to the sodium naphthionate injection into a natural swallow hole, the sampling was designed to cover potential fast flow velocities towards the Nau springs and in particular the westernmost Nauursprung spring, where one of the fluorometers was placed. The other was installed to monitor a deep artesian karst well that is used by the state water supplier. The sampling is still ongoing, but the intervals have been adapted several times since the injections. Water samples, as well as the activated charcoal adapters, are analyzed in the laboratory using a fluorescence spectrometer LS-55 from PerkinElmer (Waltham, USA).

With linear distances between injection points and the extraction wells in the Danube Valley of up to 18.5 km, the regional multi-tracer test covers a very large area. Tracer tests spanning comparable distances were undertaken by Kogovšek and Petric (2004); Petrič et al. (2018) and Fronzi et al. (2020).
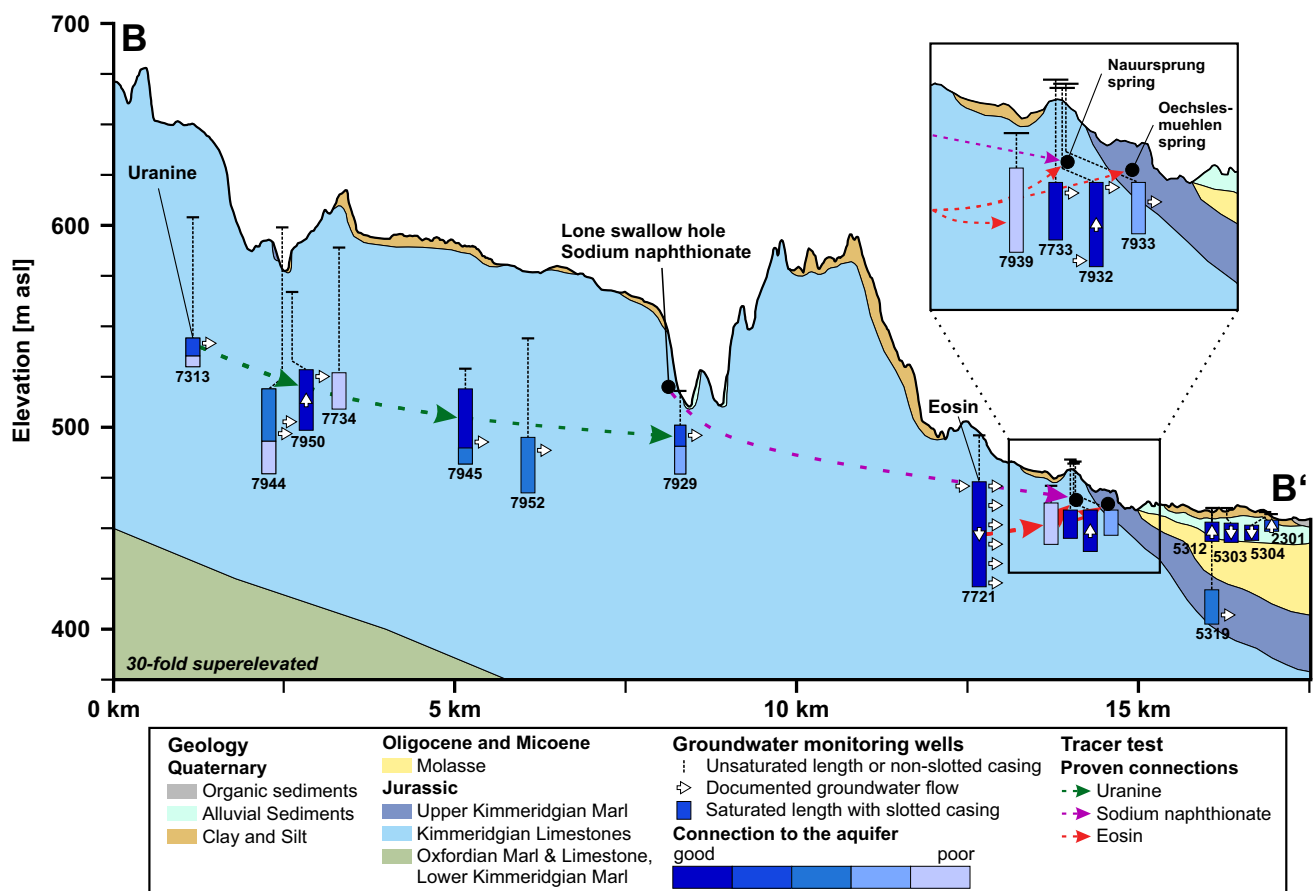

Fig. 4 Graphical overview of all SBDT results and detected connections during the tracer test. All GMWs were projected on profile B–B′ (Fig. 1) parallel to the strike of the Jurassic limestones

Table 1 Descriptive parameters of the sodium naphthionate breakthrough at Nauursprung spring (WS water samples; FF field fluorometer, V velocity, C concentration)

Parameter	Sample point		
	NU1 WS	NU1 FF	NU2 WS
Distance [m]	6,630	6,630	6,500
First detection [h]	90.4	~80	114.5
V_{max} [m/h]	73.3	~82.5	56.8
V_{peak} [m/h]	66.9	69.4	56.8
C_{max} [µg/L]	2.54	3.06	5.01
Recovery [%]	~0.03	~0.03	–

Results and discussion

Results of single-borehole dilution tests

With the SBDTs, a wide range of different flow behaviors and outflow times could be documented for the GMWs in the protection area. In Fig. 3, three examples of SBDT results from karst GMWs are displayed. Figure 3a shows the results of a point injection in GMW 7950, where a previous uniform injection indicated a good connection to the aquifer and fast outflow. The assumed vertical flow was verified with the point injection showing a clear upward movement of the tracer plume. Based on both tests, an inflow at a depth of 63 m and an outflow at around 39 m were identified. Since the decrease of salt amount during the point injection is negligible until the plume reaches the top (approx. 0.6 h), no other significant outflows are present in between. The SBDTs in GMW 7950 showed that already in the higher parts of the catchment, multiple conduit levels with different hydraulic heads exist. In this case, the higher hydraulic head in the deeper flow horizon results in upward flow within the well.

Figure 3b shows normalized concentration profiles of a uniform-injection SBDT in GMW 7945. Based on the fast decrease of NaCl concentration, the major flow horizon was identified at a depth of 36 m. After 5.25 h, the remaining salt amount was around 23% of the injected mass, indicating that the well overall shows a good connection to the aquifer. Slower outflow in the lower part was indicated by remaining NaCl concentrations 20 h after the injection. GMW 7929 (Fig. 3c) is located close to the sodium naphthionate injection point. With a uniform injection, the fastest decrease was identified at a depth of 20 m. Compared to the other two wells, the overall outflow is significantly slower. Two days after the injection, concentrations in the upper part almost reached the

Fig. 5 a Sodium naphthionate breakthrough curves (BTC) at Nauursprung spring monitored with water samples and a field fluorometer. While NU2 is a sampling point close to one of the sources, NU1 is further downstream and covers the whole spring group. **b** Shows the field fluorometer data with the fitted advection-dispersion model (ADM) curves for the three identified peaks and the wrapped curve
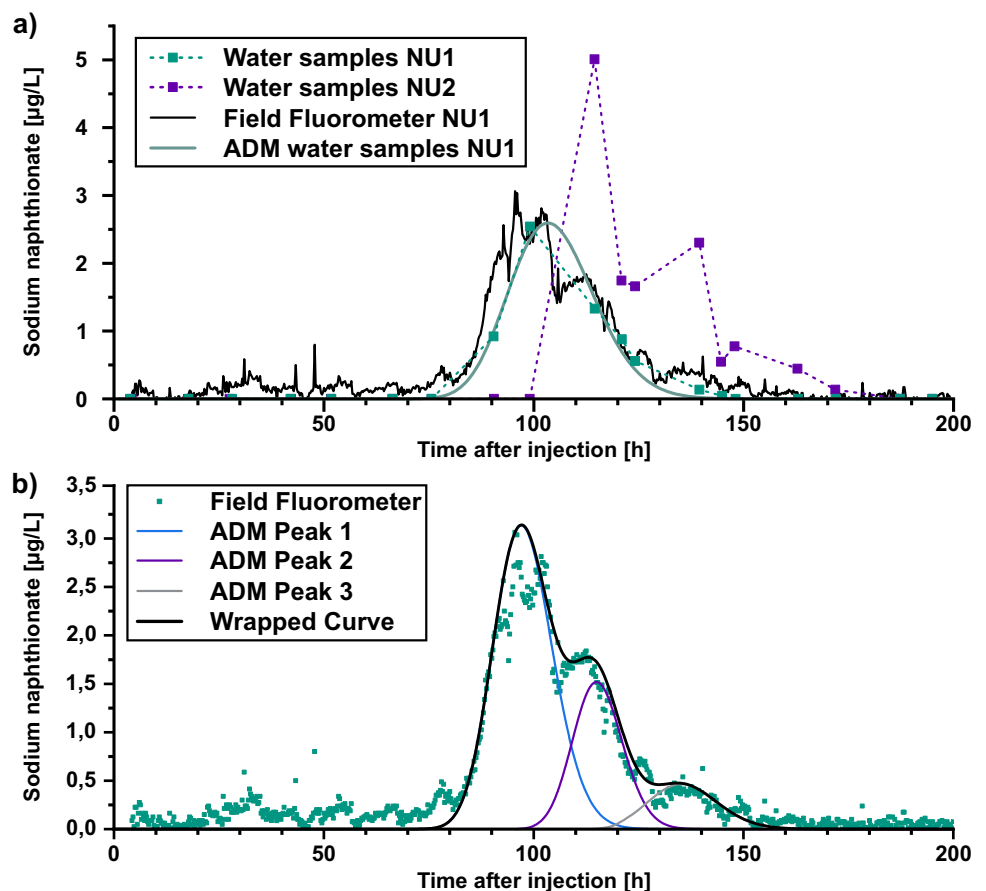
background; however, in the lower part, still around 40% of the initial concentrations were measured.

With all SBDTs a broad range of behaviors could be documented for the wells in the western part of the catchment. Half-times, the time when 50% of the tracer has flowed out of the respective well, vary between 10 min and 22 days. The longest test was monitored for more than 34 days. While the alluvial wells generally showed a faster outflow than the karst wells, some of the latter, e.g. GMW 7733 or GMW 7721, also showed an extremely good connection to the aquifer and a fast decrease in tracer amount.

Forty percent of the tested wells showed vertical flow (Fig. 4), which was mostly expected in the karst aquifer, but out of the 13 karst GMWs, only two showed an upward movement and only one showed downward flow. In the upper part of the catchment, which is the main recharge area, downward movement as part of the regional flow system was assumed. However, with the upward movement in GMW 7950, only the existence of multiple conduit levels could be documented. GMW 7721 showed a combination of vertical and horizontal flow, which fits the regional model, but might also be induced by local conditions, e.g. a stream that infiltrates into the aquifer close to the well. The upward flow in GMW 7932 suggests that karst groundwater rises in the area before the karst aquifer is overlain by the low-permeable molasse and flows towards the Nau springs or directly into the alluvial aquifer.

With regard to the alluvium, usually no distinct vertical flow would be assumed in a shallow and homogenous alluvial aquifer. However, due to the special hydrogeological setting in the groundwater protection area, with karst groundwater ascending into the alluvial aquifer, vertical flow was documented in all tested alluvial GMWs. Consequently, the two wells with upward movement are most likely located in areas with uprising karst groundwater, while downward flow in the other wells is induced by compensatory movement.

Depth-dependent outflow differences were documented in multiple wells, e.g. GMW 7313, which shows a good connection in the upper part, but in the lower part, increased NaCl concentrations were still measured 34 days after the injection. Also, wells close to each other showed different behavior.

Table 2 Descriptive parameters of the eosin breakthrough at Nauursprung spring (NU1) and Öchslesmühlen (OMS) spring

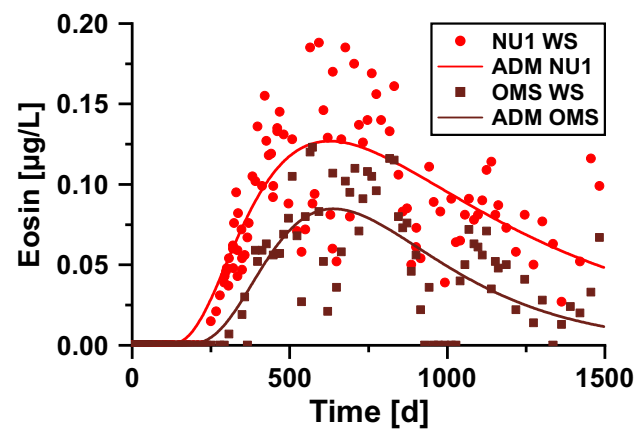| Parameter	Sampling point		
	GMW 7939	NU1	OMS
Distance [m]	1,870	2,640	2,850
First detection [days]	3	250	307
V_{max} [m/h]	26.12	0.44	0.39
V_{peak} [m/h]	26.12	0.19	0.21
C_{max} [µg/L]	0.50	0.19	0.12
Recovery[a] [%]	–	~5.1	~ 2.4

[a]Until December 2021

Fig. 6 Eosin concentrations obtained from water samples at Nauursprung spring and OMS with the respective fitted ADM curve

GMWs 7733, 7932 and 7933 form a triangle with side lengths between 50 and 60 m. Despite these small distances, each well shows a different flow behavior. GMW 7733 is well-connected to the aquifer with the major flow horizon at a depth of 29 m and no vertical flow. GMW 7932 has approximately the same outflow horizon, but also an inflow near the bottom and a resulting vertical upward movement. GMW 7933 is poorly connected to the aquifer and shows no vertical flow component. Regarding both depth and distance, these distinct differences can be explained by the characteristic heterogeneity of karst aquifers that, in this case, could be nicely documented on a small scale using borehole dilution tests.

Regional multi-tracer test

With the selected monitoring network, all three injected tracers could be detected. While sodium naphthionate and eosin arrived at the Nau springs, uranine concentrations were measured in three karst GMWs southeast of the injection well; however, no tracer has been observed in the extraction wells so far.

Ninety hours after the injection, sodium naphthionate was detected in a water sample from monitoring point NU1, which covers the whole group of sources at Nauursprung spring. With the high-resolution data of the field fluorometer, the first arrival could be determined at around 80 h (Table 1). At 114.5 h after the injection, sodium naphthionate was also detected at NU2, an additional sampling

Table 3 Summary of the uranine detections in three karst GMWs

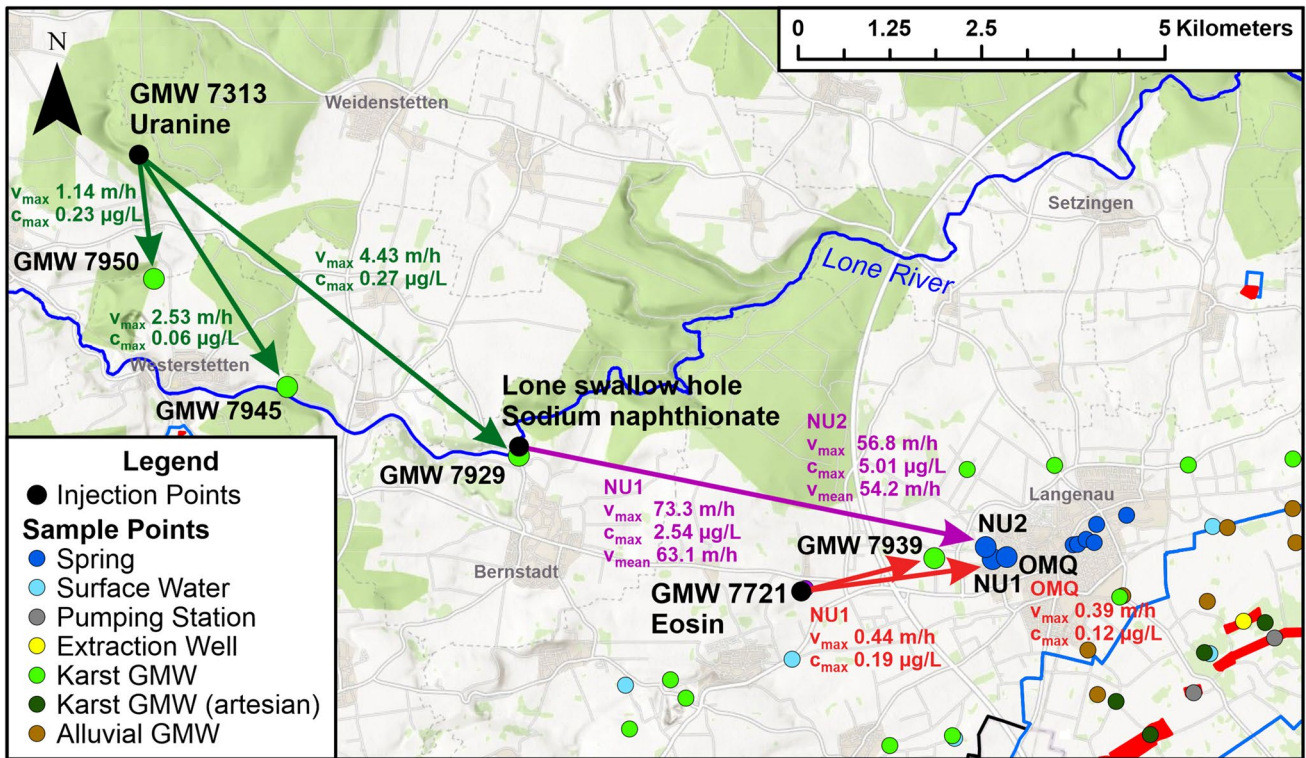| Parameter	Sampling point		
	GMW 7950	GMW 7945	GMW 7929
Distance [m]	1,700	3,760	6,590
First detection [h]	1,487.7	1,488.2	1,488.5
V_{max} [m/h]	1.14	2.53	4.43
C_{max} [µg/L]	0.23	0.06	0.27

Fig. 7 Results of the regional multi-tracer test 4 years after the injections (v_{max} = maximum velocity, c_{max} = maximum concentration, v_{mean} = mean velocity)

point upstream of NU1. This leads to the conclusion that multiple sources must exist in the area of Nauursprung spring which can also be seen based on the breakthrough curves (BTC; Fig. 5). While a high conformity of water samples and field fluorometer data is given, the latter shows three peaks. While the first peak, around 100 h after the injection, represents the first arrival at the spring group, the second peak, after ca. 115 h, can be explained through the high concentrations arriving at NU2. Due to the larger interval, this behavior is not visible in the water sample data. The same applies for the third peak after approximately 135 h.

For Nauursprung spring, a recovery rate of around 0.03% was calculated. Since no further sodium naphthionate concentrations were detected, additional flow paths have to

exist, leading towards deeper layers of the aquifer with long residence times. This explains that no other sampling point showed sodium naphthionate concentrations. Also, due to the enormous groundwater volume in the aquifer system, dilution can occur to an extent such that the concentration is below the limit of detection.

Regarding the eosin, transport towards the southeast and especially to the deep artesian karst wells was expected on the basis of groundwater-level contour lines. However, after 3 days, eosin was detected in GMW 7939, which is poorly connected to the aquifer, as shown by a SBDT (Fig. 4) and geophysical borehole logging, and located east–northeast of the injection point. At 250 days after the injection, the tracer arrived at Nauursprung spring (NU1) and after 307 days at Öchslesmühlen spring (OMS), both of which are located in a

Table 4 Summary of the modeled transport parameters for the breakthrough curves (BTCs) of sodium naphthionate and eosin

Parameter	Sodium naphthionate				Eosin	
	NU1	FF peak 1	FF peak 2	FF peak 3	NU1	OMS
Mean velocity [m/h]	63.2	67.8	57.4	45.8	0.10	0.14
Dispersion [m²/h]	1,970	1,165	492	587	54	38
Longitudinal dispersivity [m]	31.2	17.2	8.6	12.0	552.6	265.9
Dispersion parameter [−]	0.0047	0.0026	0.0013	0.0018	0.2093	0.0933
Peclet number [−]	212.7	385.8	773.4	550.2	4.8	10.7
R^2	0.9859	0.9620	0.9620	0.9620	0.8225	0.7178

Fig. 8 Relation of dispersion and velocity obtained from laboratory and field tests (modified after Strayle et al. 1994). While the sodium naphthionate breakthrough shows typical values for limestones of the Swabian Alb, both eosin breakthroughs show almost the lowest documented velocities and dispersions
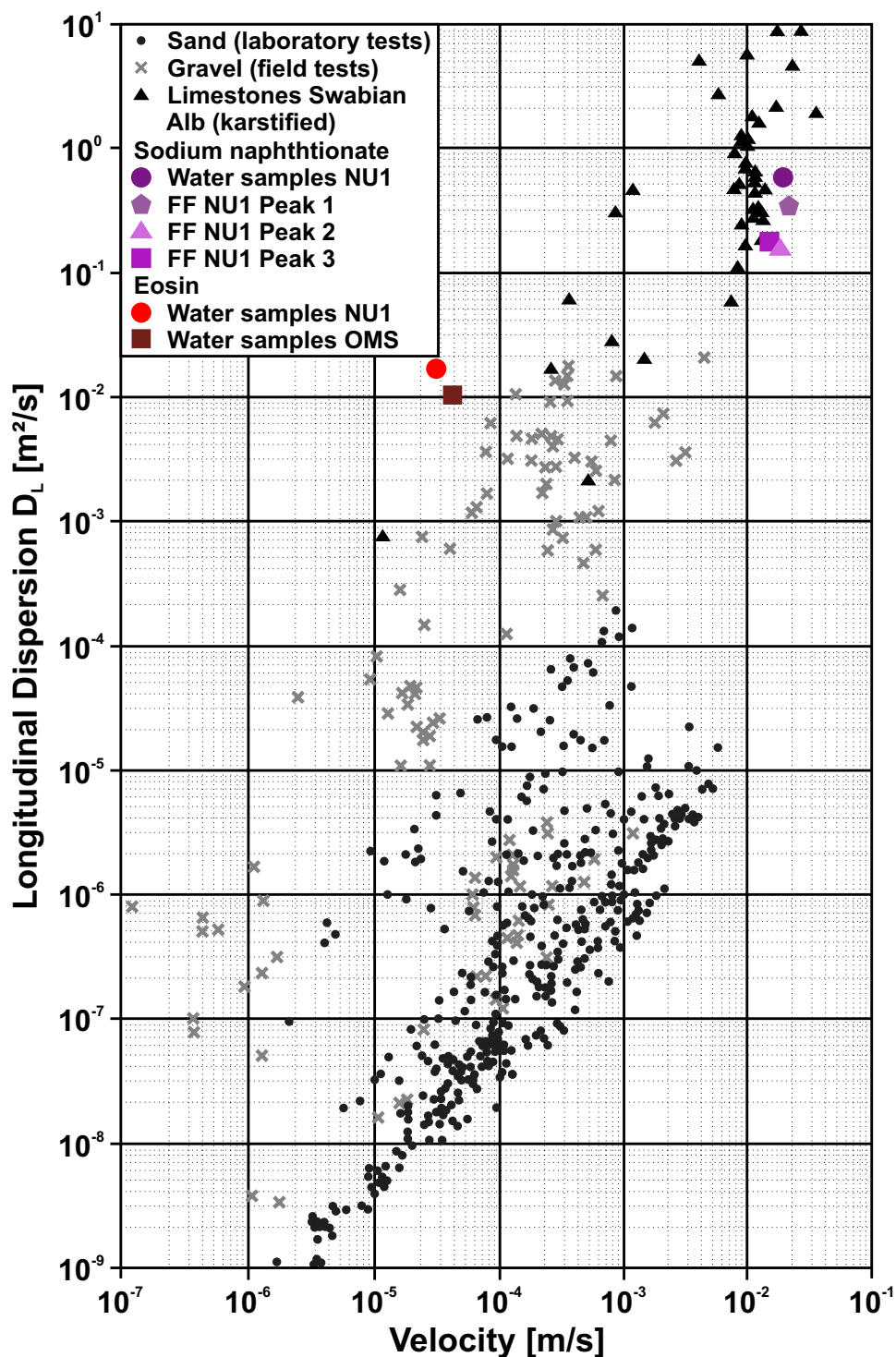
similar direction. The descriptive parameters obtained from the BTCs measured at the two springs and GMW 7939 are summarized in Table 2.

The time gap between the detection in the GMW and the springs can be explained by the geological setting in this area. Following the injection, eosin was transported towards the springs through a karst conduit that is blocked by low-permeability sediments, either molasse or Quaternary clays and silt, before the springs. This leads to an infiltration of eosin into the limestone matrix and also into GMW 7939. As the second effect of the low-permeability sediments, the further transport towards the springs is decelerated, explaining the exceptionally long travel times until the first detection and the still ongoing breakthrough.
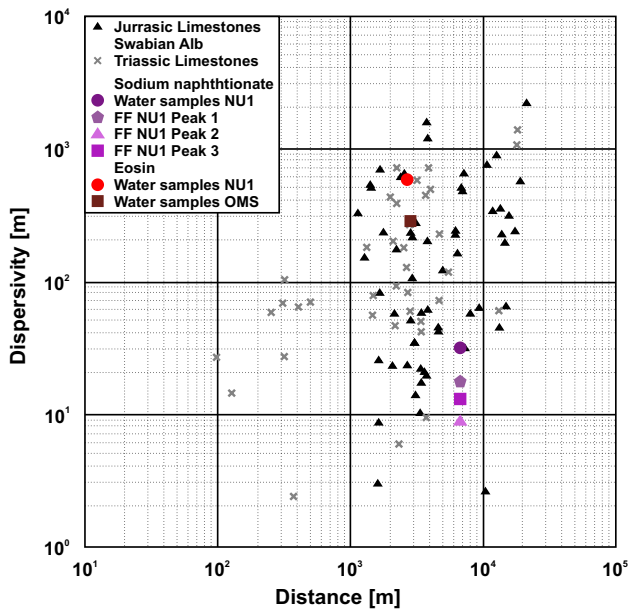
Fig. 9 Relation of distance and dispersivity for Jurassic and Triassic limestones (modified after Strayle et al. 1994). The values determined from the breakthroughs at Nauursprung spring and OMS fit well to the existing data

The eosin BTCs documented at NU1 and OMS are characterized by low and strongly fluctuating concentrations (Fig. 6) and are a result of the specific setting. Nauursprung spring covers a large catchment with different flow times, as proven by the fast arrival of sodium naphthionate; a similar situation can be assumed for the nearby OMS. This leads to varying discharge conditions and variable dilution before the tracer reaches the sampling points. A heterogenic catchment also explains why a correlation between precipitation and tracer concentrations is not possible. Additionally, minor tracer degradation via ultraviolet radiation can contribute to the fluctuations, since the eosin is exposed to sunlight between the direct sources and the sampling points. However, due to changing flow conditions and weather, this effect cannot be quantified.

Uranine concentrations were detected in GMWs 7950, 7945 and 7929, all of them located in the expected flow direction, 62 days after the injection (Table 3). During the following sampling, only GMW 7945 still showed marginal uranine concentrations. Since the dilution tests showed fast groundwater flow, especially for GMWs 7950 and 7945, it is possible that they are connected to the conduit system that transports the uranine towards the southeast. The delayed detections are most likely due to low flow velocities between the injection well and the karst conduit, but then fast transport within the conduit system.

A future detection of uranine at the springs or in the extraction wells cannot yet be ruled out. The long distance in combination with the possibility of low-permeability sediments blocking the conduits could lead to an extremely delayed arrival at the springs or wells. In addition, low-flow conditions were predominant since the injections, resulting in very low hydraulic gradients. All results of the multi-tracer test until December 2021 are summarized in Fig. 7.

The breakthrough curves documented at NU1 and OMS were modeled to obtain transport parameters. Due to the fluctuating concentrations, especially of the eosin breakthrough, a robust approach based on the advection-dispersion equation of Kreft and Zuber (1978) was chosen; the modeled curves are shown in Figs. 5 and 6, the parameters in Table 4.

For sodium naphthionate, the modeling resulted in characteristic longitudinal dispersions for limestones of the Swabian Alb: 1,970 m^2/h for the water samples and between 492 and 1,165 m^2/h for the different peaks of the field fluorometer. The eosin values until December 2021, 54 m^2/h for NU1 and 38 m^2/h for OMS, are amongst the lowest recorded in this formation, the same applies for the documented flow velocities (Fig. 8). Regarding the relation of distance and dispersivity (Fig. 9), all calculated values are within the expectable order of magnitude, only the dispersivity of the sodium naphthionate breakthroughs are a little below average.

The large-scale tracer test conducted within the scope of this project covered large distances, up to 18.5 km between injection and the extraction wells in the Danube Valley, and
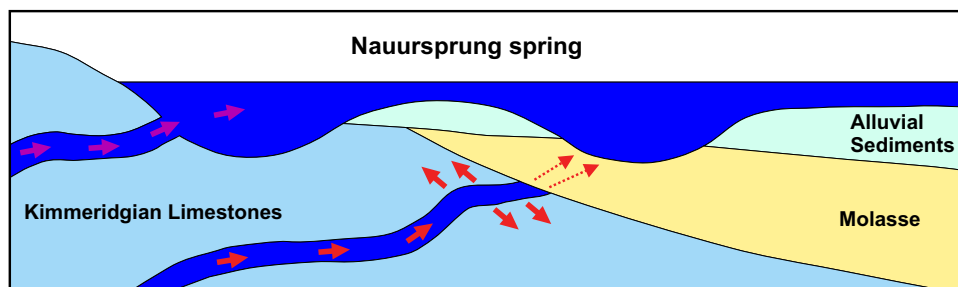

Fig. 10 Schematic interpretation of the two different behaviors documented at Nauursprung spring. The conduit transporting the sodium naphthionate opens directly into the pond, allowing fast flow and transport of dissolved substances. Other conduits are blocked by low-permeability sediments, leading to low flow velocities and a delayed arrival of eosin at the spring

showed exceptional long travel times. Comparable results were observed in the artesian karst aquifer below Stuttgart and in the Unica catchment in Slovenia, both showing breakthrough durations of more than 500 days (Goldscheider et al. 2003; Goldscheider 2008; Kogovsek and Petric 2014; Petrič et al. 2018).

With the breakthroughs at Nauursprung spring, two different behaviors could be observed. The fast arrival and the high flow velocities resulting from the sodium naphthionate injection confirm a well-developed karst conduit which must open directly into the pond. Despite a smaller distance, the eosin arrived significantly later due to low-permeability sediments blocking the conduits, resulting in a more diffuse transport pathway towards the springs. A schematic illustration of this setting is shown in Fig. 10.

Conclusions

Within this study, a complex karst and alluvial aquifer system with supraregional importance for water supply was characterized using a combination of different tracing techniques. For small-scale results, a total of 51 single-borehole dilution tests were performed in 17 groundwater monitoring wells. A regional multi-tracer test was conducted to investigate groundwater flow on a larger scale. The main conclusions are:

– The tested groundwater monitoring wells showed a wide range of results regarding connection to the aquifer and outflow behavior. Vertical flow was detected in 40% of the wells, partially caused by uprising karst groundwater in the Danube Valley. The duration of tracer outflow varied from a few hours for wells with a good connection to the aquifer and active flow horizons to more than 34 days for wells in low-permeability formations. Also, depth-dependent differences within single wells were documented.
– Several groundwater monitoring wells with a good connection to the aquifer were identified as possible injection points for large-scale tracer tests using borehole dilution tests.
– With the large-scale tracer test, variable flow systems and different hydraulic connections were documented in the study area. High karstification between a swallow hole and Nauursprung spring leads to a fast tracer breakthrough with maximum velocities of around 80 m/h. In contrast, due to low-permeability sediments, another connection to the same spring showed an exceptionally delayed arrival, with a first detection after 250 days and a maximum velocity of 0.44 m/h.
– Despite the high extraction rates, no tracer concentrations were detected in the extraction wells in the Danube Valley. This confirms long residence times and also the effectiveness of the existing protection concept; however, the hydraulic situation and the low-flow conditions must be considered for all results.

Overall, the chosen methods have proven to be applicable for an examination of a complex aquifer system. In the groundwater protection area Donauried-Hürbe, a distinct heterogeneity caused by the geological setting could be documented.

Since eosin concentrations are still being measured at the springs, more than 4 years after the injection, the sampling for the multi-tracer test is still ongoing in order to document the breakthrough completely and also to maybe detect tracer in the extraction wells. To complement the results of the western part, the project will be continued in the eastern part of the groundwater protection area with several SBDTs and a second multi-tracer test with shorter distances to the extraction wells in the Danube Valley.

Declarations

References

Banks EW, Shanafield MA, Cook PG (2014) Induced temperature gradients to examine groundwater flowpaths in open boreholes. Groundwater 52:943–951. https://doi.org/10.1111/gwat.12157

Bates B, Kundzewicz ZW, Wu S, Palutikof J (2008) Climate change and water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva

Brouyère S, Batlle-Aguilar J, Goderniaux P, Dassargues A (2008) A new tracer technique for monitoring groundwater fluxes: the finite volume point dilution method. J Contam Hydrol 95:121–140. https://doi.org/10.1016/j.jconhyd.2007.09.001

Chen Z, Auler AS, Bakalowicz M, Drew D, Griger F, Hartmann J, Jiang G, Moosdorf N, Richts A, Stevanovic Z, Veni G,

Goldscheider N (2017) The world karst aquifer mapping project: concept, mapping procedure and map of Europe. Hydrogeol J 25:771–785. https://doi.org/10.1007/s10040-016-1519-3

Delpla I, Jung A-V, Baures E, Clement M, Thomas O (2009) Impacts of climate change on surface water quality in relation to drinking water production. Environ Int 35:1225–1233. https://doi.org/10.1016/j.envint.2009.07.001

Fahrmeier N, Goeppert N, Goldscheider N (2021) Comparative application and optimization of different single-borehole dilution test techniques. Hydrogeol J 29:199–211. https://doi.org/10.1007/s10040-020-02271-2

Fahrmeier N, Goeppert N, Goldscheider N (2022) A novel probe for point injections in groundwater monitoring wells. Hydrogeol J. https://doi.org/10.1007/s10040-022-02477-6

Fronzi D, Di Curzio D, Rusi S, Valigi D, Tazioli A (2020) Comparison between periodic tracer tests and time-series analysis to assess mid- and long-term recharge model changes due to multiple strong seismic events in carbonate aquifers. Water 12:3073. https://doi.org/10.3390/w12113073

Goldscheider N (2008) A new quantitative interpretation of the long-tail and plateau-like breakthrough curves from tracer tests in the artesian karst aquifer of Stuttgart, Germany. Hydrogeol J 16:1311–1317. https://doi.org/10.1007/s10040-008-0307-0

Goldscheider N (2019) A holistic approach to groundwater protection and ecosystem services in karst terrains. Carbonates Evaporites 34:1241–1249. https://doi.org/10.1007/s13146-019-00492-5

Goldscheider N, Hötzl H, Käss W, Ufrecht W (2003) Combined tracer tests in the karst aquifer of the artesian mineral springs of Stuttgart, Germany. Environ Geol 43:922–929. https://doi.org/10.1007/s00254-002-0714-9

Haakh F (2018) Das Nitratproblem im Wasserschutzgebiet Donauried-Hürbe [The nitrate problem in the water protection area Donauried-Hürbe]. gwf-Wasser|Abwasser 12|2018:69–76

Haakh F (2019) Die Landeswasserversorgung und das Trockenjahr 2018: Analyse, Konsequenzen und Ausblick [The state water supplier Landeswasserversorgung and the dry year 2018: analysis, consequences and outlook]. LW-Schriftenreihe 2019

Hanjra MA, Qureshi ME (2010) Global water crisis and future food security in an era of climate change. Food Policy 35:365–377. https://doi.org/10.1016/j.foodpol.2010.05.006

ISO.org (2021) Online browsing platform. https://www.iso.org/obp/ui/#search/code/. Accessed Feb 2021

Kogovšek J, Petric M (2004) Advantages of longer–term tracing: three case studies from Slovenia. Environ Geol 47:76–83. https://doi.org/10.1007/s00254-004-1135-8

Kogovsek J, Petric M (2014) Solute transport processes in a karst vadose zone characterized by long-term tracer tests [The cave system of Postojnska Jama, Slovenia]. J Hydrol 519:1205–1213. https://doi.org/10.1016/j.jhydrol.2014.08.047

Kolokotronis V, Plum H, Prestel R, Schloz W, Rausch R (2002) Hydrogeologische Karte von Baden-Württemberg. Ostalb. Erläuterungen [Hydrogelogical Map of Baden-Württemberg. Eastern Swabian Alb. Explanation]. Landesamt für Geologie, Rohstoffe und Bergbau Baden-Württemberg, Freiburg i.Br.; Landesanstalt für Umweltschutz, Baden-Württemberg, Karlsruhe, Germany

Kreft A, Zuber A (1978) On the physical meaning of the dispersion equation and its solutions for different initial and boundary conditions. Chem Eng Sci 33:1471–1480. https://doi.org/10.1016/0009-2509(78)85196-3

Libby JL, Robbins GA (2014) An unsteady state tracer method for characterizing fractures in bedrock Wells. Groundwater 52:136–144. https://doi.org/10.1111/gwat.12045

Maurice L, Barker JA, Atkinson TC, Williams AT, Smart PL (2011) A tracer methodology for identifying ambient flows in boreholes. Ground Water 49:227–238. https://doi.org/10.1111/j.1745-6584.2010.00708.x

Olmstead SM (2014) Climate change adaptation and water resource management: a review of the literature. Energy Econ 46:500–509. https://doi.org/10.1016/j.eneco.2013.09.005

Petrič M, Kogovšek J, Ravbar N (2018) Effects of the vadose zone on groundwater flow and solute transport characteristics in mountainous karst aquifers: the case of the Javorniki–Snežnik massif (SW Slovenia). AC 47. https://doi.org/10.3986/ac.v47i1.5144

Poulsen DL, Cook PG, Simmons CT, McCallum JM, Noorduijn SL, Dogramaci S (2019) A constant rate salt tracer injection method to quantify pumped flows in long-screened or open borehole wells. J Hydrol 574:408–420. https://doi.org/10.1016/j.jhydrol.2019.04.051

Read T, Bour O, Selker JS, Bense VF, Borgne TL, Hochreutener R, Lavenant N (2014) Active-distributed temperature sensing to continuously quantify vertical flow in boreholes. Water Resour Res 50:3706–3713. https://doi.org/10.1002/2014WR015273

Schloz W, Armbruster V, Prestel R, Weinzierl W (2007) Hydrogeologisches Abschlussgutachten zur Neuabgrenzung des Wasserschutzgebietes Donauried-Hürbe für die Fassungen des Zweckverbandes Landeswasserversorgung im württembergischen Donauried und bei Giengen-Burgberg [Hydrogeological report on the new demarcation of the water protection area Donauried-Hürbe for the well fields of the state water supplier Zweckverband Landeswasserversorgung in the Danube Valley in Württemberg and near Giengen-Burgberg]. Regierungspräsidium Freiburg, Landesamt für Geologie Rohstoffe und Bergbau

Stevanović Z (2019) Karst waters in potable water supply: a global scale overview. Environ Earth Sci 78:662. https://doi.org/10.1007/s12665-019-8670-9

Strayle G, Stober I, Schloz W (1994) Ergiebigkeitsuntersuchungen in Festgesteinsaquiferen [Productivity investigations in bedrock aquifers]. Geologisches Landesamt Baden-Württemberg, Freiburg, Germany

Udluft P, Bühlmeier C, Schäfer U, Wimmer M, Kus G, Aulbach E, Winter J (2000) Das Grundwasser im schwäbischen Donautal: hydrologisch-hydrogeologische Untersuchung mit Erstellung eines Grundwassermodells im Maßstab 1:25000/50000 im Donautal zwischen Ulm/Neu-Ulm und Neuburg an der Donau [The groundwater in the Swabian Danube Valley: hydrological-hydrogeological investigation with generation of a groundwater model on a scale of 1:25000/50000 in the Danube Valley between Ulm/Neu-Ulm and Neuburg an der Donau]. Ludwig Auer, Munich, Germany

West LJ, Odling NE (2007) Characterization of a multilayer aquifer using open well dilution tests. Ground Water 45:74–84. https://doi.org/10.1111/j.1745-6584.2006.00262.x

Wheeler T, von Braun J (2013) Climate change impacts on global food security. Science 341:508–513. https://doi.org/10.1126/science.1239402

World Bank (2016) High and dry: climate change, water, and the economy. World Bank, Washington, DC

Zweckverband Landeswasserversorgung Stuttgart (ed) (2012) Landeswasserversorgung 100 Jahre Trinkwasser für Baden-Württemberg 1912–2012 [State water supplier Landeswasserversorgung 100 years drinking water for Baden-Württemberg 1912-2012]. Stuttgart, Germany

Zweckverband Landeswasserversorgung Stuttgart (2021) Homepage. https://lw-online.de. Accessed July 2022