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TECHNICAL NOTE

A novel probe for point injections in groundwater monitoring wells

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Abstract

Groundwater monitoring wells or boreholes often show complex flow behaviors that are essential to understand for the characterization of aquifer systems. In karst or fractured aquifers, where complex conduit and/or fracture networks with differing hydraulic heads can be intersected by a well or borehole, vertical flow is highly probable. Single-borehole dilution tests (SBDT) with uniform injections are, in general, a good method to gain knowledge about a specific well or borehole, but tend to deliver ambiguous results regarding vertical flow, while SBDTs with point injections are an effective method to identify vertical flow. This technical note introduces a newly developed probe for point injections in groundwater without disturbing the natural flow field. In order to evaluate this probe, several tests were conducted in the laboratory and in groundwater monitoring wells that show vertical flow. During repeated tests in the laboratory, the new point injection probe showed a good reproducibility regarding the shape and extent of the tracer cloud after an injection. The opening mechanism was found to be well-functioning and reliable. Field tests lead to significant results for all tested wells and showed that the probe can easily be operated by a single person. Due to the flexibility regarding tracer, aquifer and injection depth, combined with the easy handling, it is a useful device, suitable for the investigation of boreholes and groundwater monitoring wells, and a good alternative to existing methods.

Keywords Groundwater flow · Borehole techniques · Tracer tests · Single-well method · Point injection

Introduction

In-situ characterization of groundwater flow is important for the understanding of complex aquifer systems. A wide range of geophysical, hydraulic and tracer-based methods is available to examine aquifer properties and groundwater flow directly in the aquifer. For the investigation of flow systems in boreholes or groundwater monitoring wells (GMW), distributed temperature sensing has been widely used in the last years (Leaf et al. 2012; Banks et al. 2014; Read et al. 2014; Sellwood et al. 2015; Bense et al. 2016). One other efficient and practicable method that delivers important and useful results about groundwater flow is single-borehole dilution tests (SBDTs). Uniform tracer injections throughout the entire saturated length deliver information about the whole groundwater monitoring well or borehole and can be achieved with several methods, for example by the use of hosepipes, often combined with pumping (Hall 1993; West and Odling 2007; Shafer et al. 2010; Maurice et al. 2011; Libby and Robbins 2014). Alternatively, the new method introduced by Fahrmeier et al. (2021), which uses a permeable injection bag, can be used.

The results of uniform injections for one particular depth are not always representative for the entire borehole, and vertical flow components are not always identifiable. In these cases, point injections can be used to complete the information gained by uniform injections, whereby the results of the uniform injection can be used to determine the depth for a point injection (Maurice et al. 2011). Information about vertical flow is important for the understanding of the processes within boreholes or GMWs and can also contribute to the understanding of complex aquifer systems. Especially karst and fractured aquifers often show vertical flow, due to the compensation of different pressures in solutionally enlarged fractures and bedding planes that are intersected by the boreholes or GMWs (Michalski and Klepp 1990). Additional to information about vertical flow, point injections can also be used for the characterization of one specific depth, if the productivity or flow rate of this depth is of particular interest.

Common methods for characterizing a specific depth in a borehole or GMW use systems with two packers that enclose

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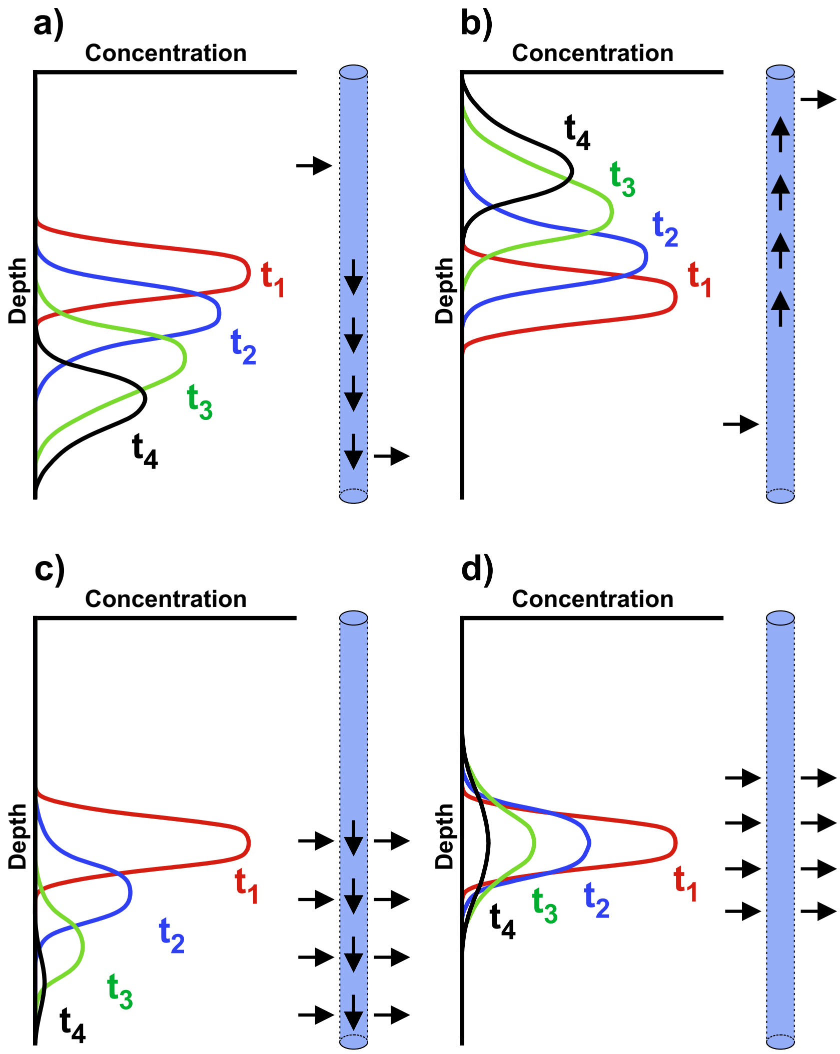

Fig. 1 Four typical concentration patterns after point injections in groundwater monitoring wells. Curve t1 shows the ideal salt plume after the injection, and t2, t3 and t4 show the development of the salt plume at increasing times, induced by groundwater flow in the well

a depth interval which then can be tested. Most of these systems inject the respective tracer directly in the test chamber where it is continuously mixed, either using a pump or a mixing unit (e.g. a propeller), and also directly measured with a measuring device placed in the test chamber (Drost et al. 1968; Grisak et al. 1977; Palmer 1993; Novakowski et al. 2006; Gouze et al. 2008; Yang et al. 2019; Devlin 2020). A modified version continuously circulates water from the interval between the packers to the surface and back. During this circulation, the tracer is added, and afterwards the concentration is monitored with an in-line device (Jamin et al. 2015).

Other point injection methods, without the use of packers, deliver results for the whole well or borehole. Poulsen et al. (2019) use a continuous injection of tracer in one specific depth, combined with pumping near the top of the well. This allows one to draw conclusions on all flowing features between injection and extraction depth. Related methods were used by Brouyère et al. (2008), Leaf et al. (2012) and Read et al. (2015); however, due to the pumping, natural vertical flow is not visible or at least strongly influenced.

All these methods are not suitable to investigate and characterize the natural in- and outflow behavior of GMWs or boreholes completely, since they affect the natural flow system due to pumping or blocking vertical flow with hydraulic packers. If vertical flow is to be taken into account, it is necessary to have a point injection under natural gradient conditions, without pumping influences or packers. Injecting tracer under natural-gradient conditions reveals vertical flow by an up- or downward movement of the tracer plume. Figure 1 shows typical movements of a tracer plume after a point injection under natural conditions, depending on the water movement within the well or borehole, and Fig. 1a displays a well with downward flow and one outflow zone near the bottom, and Fig. 1b shows upward flow in combination with a single outflow zone near the top. Figure 1c shows downward flow in combination with horizontal flow, which leads to a faster reduction of the tracer in the well, while Fig. 1d displays a well without any vertical flow but horizontal outflow at the depth of the tracer cloud. In this case, the tracer plume remains at the injection depth and the peak just widens a little, due to diffusion.

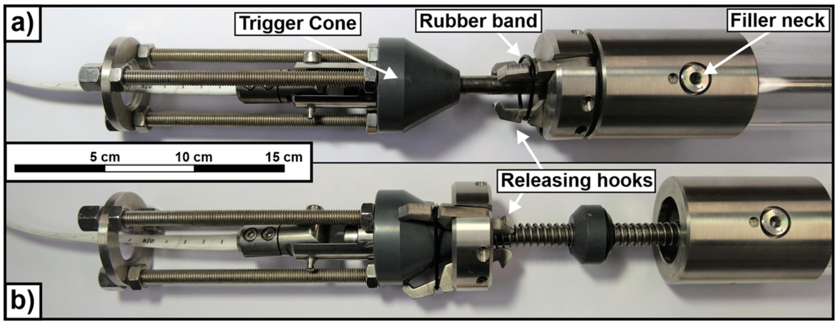

Fig. 2 Detailed view of the **a** closed and **b** opened injection probe. When the trigger cone is pushed down, it opens the three hooks, which allows the casing to slide down

Different devices can be used to achieve a point injection under natural flow conditions. Pitrak et al. (2007) used a specially designed tool consisting of a thin plastic hose connecting two syringes with a volume of 20 ml; one is kept at the surface, the other one is lowered into the selected depth. Pushing the first syringe leads to a release of the tracer from the second syringe. Tate et al. (1970) introduced an injector with a cylindrical container and an electromagnetic opening mechanism. When this mechanism is triggered, the outer part of the container sinks down and releases the tracer into the groundwater.

This technical note introduces a newly developed probe for point injections in groundwater that does not disturb the natural flow or prevent vertical flow components. In order to evaluate the point injection probe, several tests were conducted in the laboratory and in groundwater monitoring wells that show vertical flow.

Point injection probe

The concept of the new point injection probe is based on depth-dependent sampling devices which are opened or closed by a falling weight. Based on this idea, and in cooperation with a precision engineer, the injection probe was designed. It consists of a container with a movable outer casing and a mechanical opening mechanism on top, that is attached to a measuring tape, along which a falling weight is dropped down to trigger the opening mechanism. Figure 2 shows pictures of the probe in a closed and opened state. The container is held together by three hooks, fixed by a rubber band. When the trigger cone is pushed down, it overcomes the strength of the rubber band, causing the hooks to unlock the container's casing, which then slides down and releases the tracer in the surrounding groundwater (Fig. 3a).

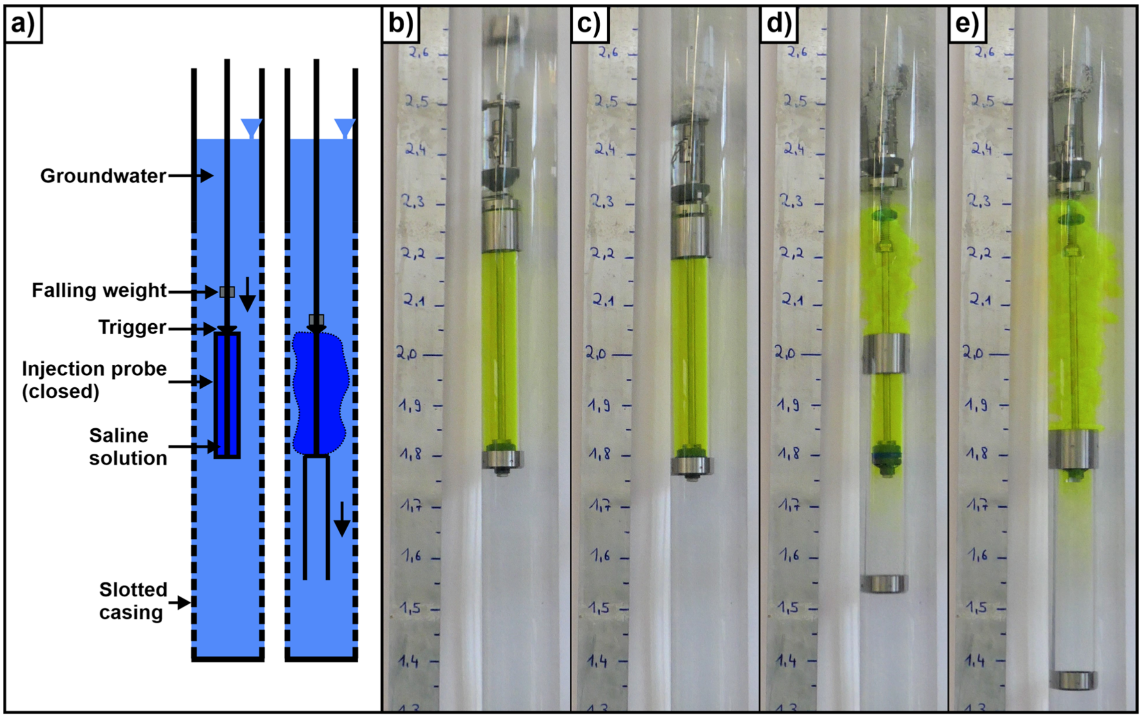

Fig. 3 **a** Illustration of a point injection using the new probe; **b**–**e** pictures of an injection using Uranine in the acrylic glass well in the laboratory: **b** shows the closed probe directly before the falling weight hits the mechanism, **c** is in the exact moment when the opening mechanism is triggered; **d** the picture shows the probe already halfway open, and **e** shows the completely opened probe

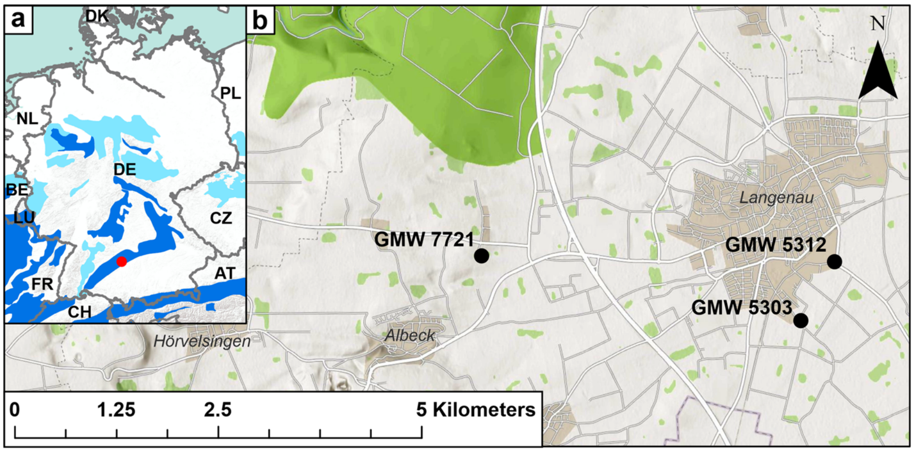

Fig. 4 **a** Location of the study site shown on a cut-out of the World Karst Aquifer Map (WOKAM, Chen et al. 2017; dark blue: continuous carbonate rocks, light blue: discontinuous carbonate rocks; country codes from ISO.org (2021)). **b** Locations of the three groundwater monitoring wells (GMWs) used for the evaluation of the point injection probe

With the help of a funnel, the probe can be filled with tracer solution through the filler neck near the top, using any kind of soluble tracer, e.g. NaCl or fluorescence dyes. The container was configured with a capacity of 500 ml, a length of 50 cm and a diameter of 6 cm. Due to the small diameter, the point injection probe can be used in all wells or boreholes with a diameter larger than 3 in. (7.6 cm).

Figure 3 shows the probe during an injection in the laboratory using uranine for better visibility. Figure 3b shows the closed probe immediately before the weight hits the opening mechanism, while Fig. 3c displays the exact moment the opening mechanism is triggered and Fig. 3d shows the casing dropping down and releasing the tracer into the surrounding water. The final stage of the injection with the completely opened probe can be seen in Fig. 3e. The entire opening process takes around 1.5 s.

Test sites

The new point injection probe was tested under laboratory conditions, as well as in groundwater monitoring wells in the field. The laboratory experiments were conducted in a transparent acrylic glass tube with a length of 6 m. The tube was filled with water and used for several injections, to test the probe under perfectly-controlled no-flow conditions and to check the injection mechanism visually. Field tests were conducted in the groundwater protection area of a large water supplier in South Germany (Fig. 4), which contains a complex aquifer system and was already investigated with a large-scale multitracer test and several SBDTs (Fahrmeier et al. 2021). The combination of the large karst aquifer with the overlying gravel aquifer leads to vertical flow in several groundwater monitoring wells. Since both downward and upward flows occur, this area was chosen for the field tests of the new probe.

Results and discussion

Laboratory tests

To check and evaluate the point injection probe under completely undisturbed conditions, repeated tests were conducted in the acrylic glass tube in the laboratory. Based on the observation of these tests, it was possible to make some adjustments for a better functionality of the opening mechanism. Since the acrylic glass tube has no outflows or vertical flows, injections at the same depth using the same tracer quantity should ideally result in identical concentration profiles. Knowing the shape of the injection curve allows a correct interpretation of the movement of the tracer plume as well as clarification as to whether vertical flow is present or not. It is

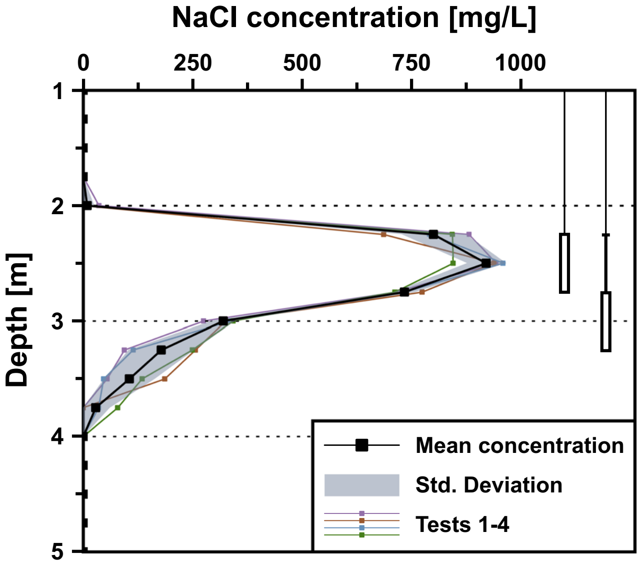

Fig. 5 Concentration profiles of repeated point injections under laboratory conditions, measured immediately after tracer release. For each injection, the probe was filled with 500 ml of a 25 g/L NaCl solution. The standard deviation of the four profiles between 2 and 3.75 m is 11%, while the accuracy of the TLS Meter is at 5%. On the right side, the depths of the closed and opened probe are indicated

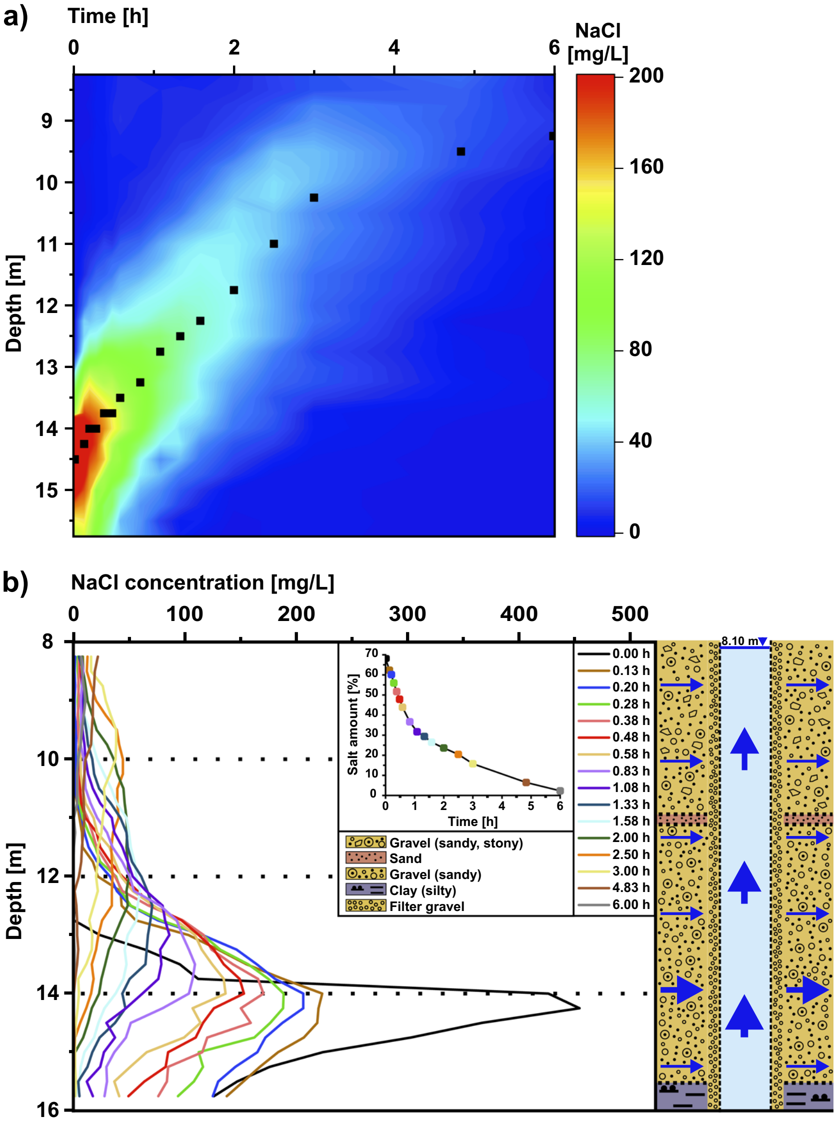

Fig. 6 Point injection in GMW 5312 (18.11.2020); 12.5 g NaCl (500 ml of a 25 g/L solution) were injected at a depth of 14 m. **a** The salt plume shows upward movement within the well, the black squares indicate the center of the salt plume for each measurement. **b** The fast decrease of salt amount reveals an additional horizontal outflow. The arrows on the right display the groundwater flow within the well derived from the concentration profiles

also important for the comparison of different tests. Figure 5 shows profiles of NaCl concentrations measured directly after the injections using an electrical conductivity meter (TLC Meter Model 107, Solinst Ltd., accuracy of 5% or 100 µS/cm). During measurements, in the laboratory as well as in the field, the TLC Meter was moved carefully, while avoiding sudden and fast movements, to minimize mixing within the well. With a relation of cross-section areas of 1:50–1:70, the impact on the natural water flow is negligible.

The resulting curves show a high conformity and a standard deviation of 44 mg/L from the mean value, indicating that the probe always creates the same injection profile under undisturbed conditions, which is essential for further use. To evaluate further, R^2 and RMSE were calculated for each pair of injection profiles, resulting in mean values of 0.9734 and 45.6, respectively. As intended, the highest tracer concentration was always measured at the depth where the middle of the closed probe was placed. The salt plume extends vertically about 1.5–1.75 m for each test, which still can be considered as a point injection, especially in deep wells. The asymmetry in the lower part might be induced by the downward movement of the container, as well as by the movement of the electrical conductivity meter during the measurement.

Field tests

After the tests in the acrylic glass tube, the point injection probe was used for point injections in three groundwater monitoring wells on the Swabian Alb, where previous research has revealed vertical flow (Fahrmeier et al. 2021). Measurement intervals for each GMW were chosen based on the movement of the salt plume and adapted during the tests. Figure 6a shows a contour plot of an SBDT in GMW 5312, where 12.5 g NaCl

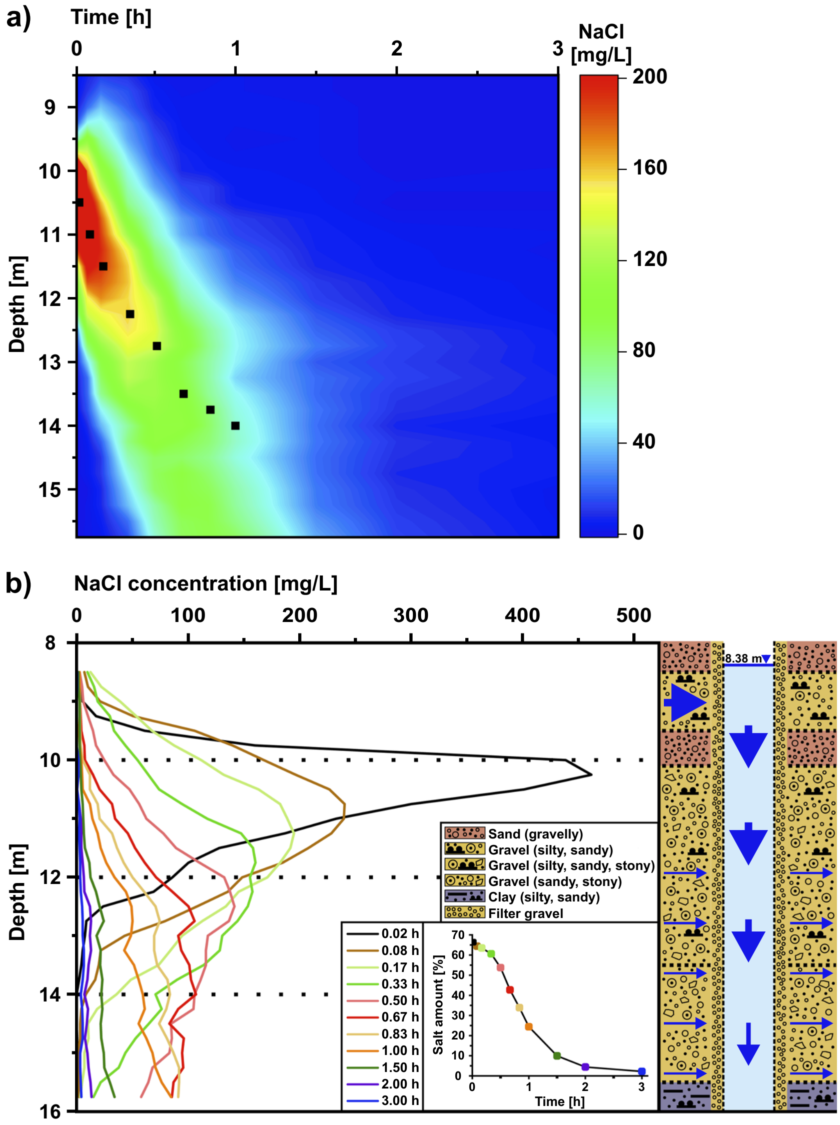

Fig. 7 Point injection in GMW 5303 (18.11.2020); 12.5 g NaCl (500 ml of a 25 g/L solution) were injected at a depth of 10 m. **a** The tracer plume shows a fast downward movement, and **b** the salt amount indicates a delayed outflow due to the injection in the upper part of the well and the main outflow in the lower part

(500 ml of 25 g/L solution) were injected at a depth of 14 m (all depths refer to the respective well cap; injection depths indicate the depth of the middle of the closed probe). The black squares indicate the center of the salt plume for each measurement.

At the first measurement, the salt plume extends about 2.5 m (Fig. 6b), which is larger than the same taken during the tests done in the laboratory. The extent of the plume is caused by vertical flow, which is demonstrated by the next measurements that show a clear upward movement of the salt plume. Based on the vertical offset between the maximum concentrations for each measurement, or alternatively based on the offset of the center of the tracer cloud, the vertical upward flow can be estimated at around 1.5 m/h. Directly from the beginning, the salt amount shows a rapid decrease, which indicates an additional horizontal flow in the lower part of GMW 5312.

In contrast, Fig. 7 shows an example with vertical downward flow from GMW 5303, where 500 ml of a 25 g/L NaCl solution were injected at a depth of 10 m. GMW 5303 shows a rapid downward flow, which already influences the first profile. The following measurements demonstrate the fast vertical flow in the well by the downward movement of the salt plume. The velocity of the downward flow can be estimated at 5.7 m/h, based on the mean vertical offset between the measurements.

The development of tracer amount over time shows just a slow decrease in the first 20 min. Then, as soon as the tracer plume reaches depths below 12 m, the decrease gets faster, indicating a higher outflow in the lower part of the well. The higher outflow near the bottom can be explained by a higher permeability due to less fine-grained sediments (silt) at this depth. Three other point injections in GMW 5303 in 2018 and 2020 showed similar results. Depending on water level, injection depth and distance to the zone with higher outflow, the half-time (time until 50% of the trace has left the well) varies between 11 min and 1.5 h.

The third example (Fig. 8) displays an injection in GMW 7721, which is a karst well with a total depth of 74 m and an already demonstrated vertical flow (Fahrmeier et al. 2021). After the tracer was injected at a depth of 31 m, the salt plume moves downward, and after 9 h the maximum value is near the bottom of the well. Based on the mean offset, the vertical flow has a velocity of approximately 3.8 m/h.

Up to the third measurement, the salt amount shows a strong decrease, which is then decelerated and almost constant, indicating a strong horizontal flow in the upper part of the well, most likely in the limestone above the clay layer. Below this zone, since the salt amount shows a continuous decrease, horizontal flow is less strong but uniform in every depth. An earlier test with an impeller flowmeter was not able to detect the vertical flow in GMW 7721, since the velocity was too low for the impeller to turn, which is a common problem with these devices (Sellwood et al. 2015). This shows that point injection-SBDTs are better at detecting low velocities. Alternatively, an electromagnetic flowmeter or a heat pulse flowmeter could have been used; however, the latter is used in a stationary position and would require several measurements to deliver results for an entire well (Sellwood et al. 2015).

Conclusion

The new probe for point injections in groundwater monitoring wells and boreholes was tested in the laboratory and in the field. The results showed a good reproducibility regarding the shape and extent of the tracer cloud, which proves the suitability of the probe. It is robust and equipped with a well-

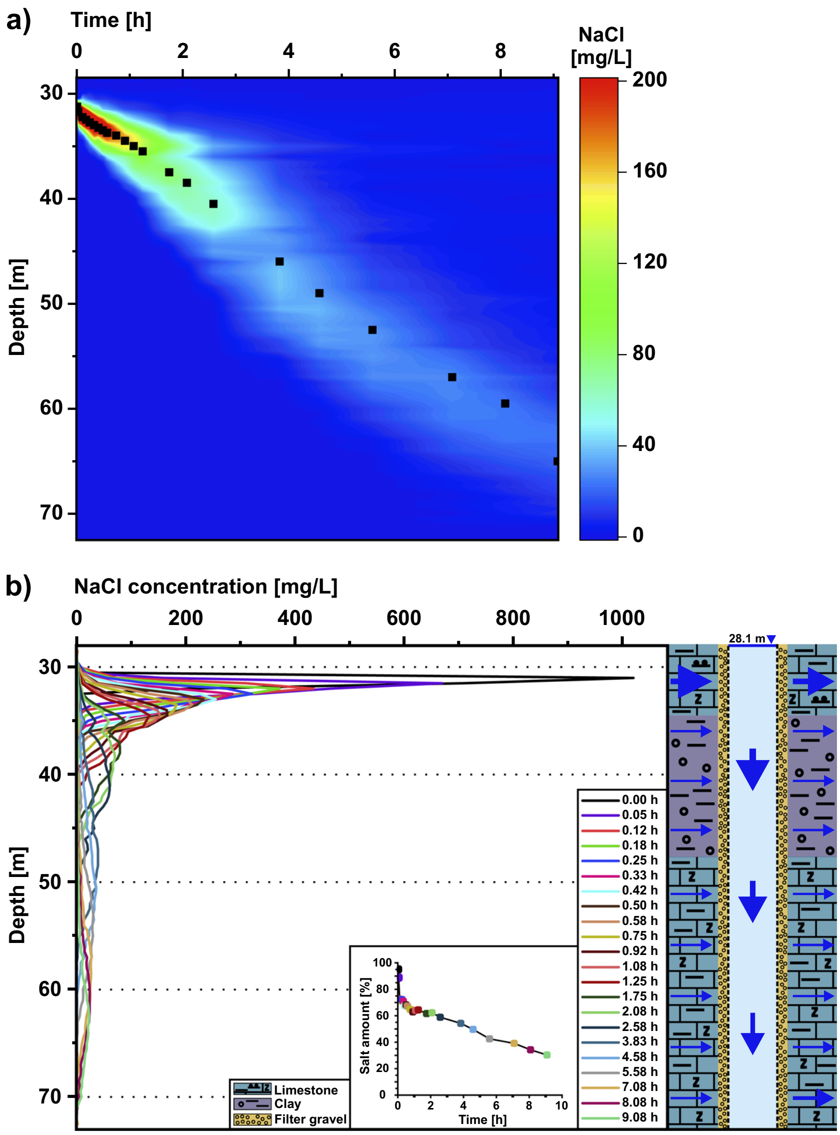

Fig. 8 Point injection in GMW 7721 (17.11.2020). 12.5 g NaCl (500 ml of a 25 g/L solution) were injected at a depth of 31 m. **a** The salt plume moves downward at a steady speed, indicated by the center of the salt plume for each measurement (black squares). **b** A zone with high outflow in the upper part (ca. 30–33 m depth) is identifiable through the fast decrease of the salt amount during the first measurements

functioning and reliable opening mechanism. Due to its simplicity, the mechanical mechanism is an advantage compared to existing devices. Also, the probe is easy to handle, can be operated by one person, and is designed to minimize effects on the natural flow within the GMW or aquifer; thus it is particularly suitable if vertical flow is relevant and should be observed. Using the new probe, it is not possible to gain absolute velocities for vertical flow, but due to the tracer movement and the shifting of the maximum concentration or the center of the tracer cloud, an approximate value can be estimated. As an advantage over impeller flowmeters, which are not able to detect low vertical velocities, even minimal vertical flow rates can be documented. Compared to other devices and methods, SBTDs with the new point injection probe need less personnel and less equipment; no pump or electricity is needed, just the probe, tracer (typically NaCl) and a measuring device. This reduces costs and makes the point injection probe suitable for many applications, e.g. study areas with a large number of monitoring wells, and accordingly many necessary tests, but also projects in low-income countries or projects with limited resources. Due to the good portability, it is also practical for testing locations that are difficult to access. Additionally, the length of the measuring tape is flexible, so the probe can be used in deep wells without depth limitation and without being adapted for each well, which is an advantage compared to existing methods or devices.

With the salt plume extending over 1.75 m for an undisturbed injection profile, it can be considered as a point injection in most wells or boreholes. If the diameter of the tested well or borehole is big enough, the probe preferably remains at the injection depth during the measurements to avoid turbulences that would influence the test. If the diameter is smaller than 10 cm, the probe should be carefully lowered to the bottom of the well or borehole before starting the measurements.

If NaCl is used as a tracer, low concentrations, e.g. 25 g/L, should be used to avoid or minimize density effects. With uranine or other fluorescence tracers, density effects can be completely avoided, due to the lower concentrations, but more expensive measuring equipment is required. Diffusional influences are negligible for wells with a good connection to the aquifer, since diffusion is a much slower process compared to groundwater flow. To prevent turbulences induced by the measurements, multiple divers can be preinstalled at fixed depth intervals. Although it does not generate complete profiles, up- or downward movement can be detected this way.

In summary, the new point injection probe is a useful device and a good alternative to the existing methods. Due to the flexibility regarding tracer, aquifer and injection depth, combined with easy handling, it is suitable for the investigation of boreholes and groundwater monitoring wells, which is why a patent has been applied for the probe.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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