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Preparation and Hydrogeological Evaluation of Tracer Experiments

Vorbereitung und hydrogeologische Auswertung von Markierungsversuchen

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Content

1. Indroduction

Water constitutes a fundamental precondition for the development of natural landscape. The growing demand on quality and quantity of water is closely connected with the intensification of human activities. The complex study of the hydrological cycle in both its surface and underground parts provides the required information for the realization of these activities. While the surface waters are readily accessible to our observations, the study of groundwater involves the application of time-consuming procedures and methods, which overcome the "invisibility" of these waters. At the same time, the utilization of groundwaters for supplying the population has a primary importance in comparison with surface water owing to the lesser probability of their vulnerability. Tracer methods constitute an important identification procedure for the assessment of objectively measurable characteristics of groundwater bodies. The application results of these methods are able to quantify the share of groundwater in the natural hydrological cycle and render it more accurate.

The principle of tracing methods is based on the tagging of a flowing medium by a tracer, which is traced in dependence of time at the indication site or at observation points (spring, bore hole, water course). The tracing methods can be divided in distance (multi-point) methods and single-well ones – according to the tracer detection sites. The single-well method does not allow to follow the

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connections and flow directions of groundwater in hydrogeological structures. The distance method gives unambiguous evidence on continuities and flow directions of groundwater. The effectiveness of each tracing method is determined by finding the tracer at the observation point. Not any finding of a tracer can be regarded as conclusive, it has only speculative significance.

The distance method is the most frequently used tracing method for the determination of continuities, velocities and directions of groundwater flow. Adjoined to this method can also be the method of regional tracers; for investigating the retention time of groundwater in large hydrogeological structures and regions, they use light natural nuclides, such as carbon-14, silicon-32, oxygen-18, deuterium, and others as tracers.

2. Characteristics and Application of Tracers

A tracer is a substance naturally contained in or artificially added to a water-bearing environment, which the water flow should be traced for in natural conditions. This definition implies the fact that only some special substances are suitable for the given purpose. An ideal tracer should possess the following properties: conformity of motion with the water flow, suitable physico-chemical properties (good solubility or formation of suspensions, resp., inertness towards rock environment and water, low absorption, minimum contamination of the equipment, small size of molecule), a low perception limit, quick and sensitive determination, very low concentration in natural waters, very low environmental and sanitary harmfulness, a low price.

We are also able to distinguish classic and radioactive tracers. Among the classic ones, the solid tracers of organic origin (spores, bacteria, yeasts, and others) and suspensions may be ranged. These substances can be applied only in rocks with karstic (channel) permeability. Chemical tracers are represented by anorganic salts (anions, cations) and organic dyestuffs. Owing to their affinity to adsorption, some cations (NH_4^+, Fe^{2+}, Cu^{2+}, Ni^{2+}) can be used only in rocks with high permeability (J. HANZLÍK & I. LANDA, 1980). The application of anions is more advantageous, because they are chemically stable, less prone to sorption in the rock environment, and can be determined with sufficient precision by simple procedures. A high initial dosage of salts given by the natural concentration of anions in water acts as an unfavourable factor.

Among anions, the chloride, nitrite, and nitrate ions proved useful in measurements of water flow velocity in collectors with a high portion of clayey components and an irregular development of arenaceous positions (J. HANZLÍK, 1973). Organic dyestuffs, such as fluoresceine, uranine, eosine, and others have only limited applicability in collectors with a clayey component, which is due to their high adsorption in such conditions. The suitability of tracers for the measurement of the flow rate of the groundwater is illustrated by fig. 1 and 2. The advance of two different tracers has been studied on a model filled with natural sand ($D = 2.72$), the sampling from six different height levels at varying gradient conditions. Fluoresceine proved to be a less suitable tracer, as its breakthrough curves did not exhibit marked peaks, unlike the ones of chloride ions.

A single application of classic tracers mostly changes the specific weight of the traced water due to the addition of a larger volume of concentrated tracer solution.

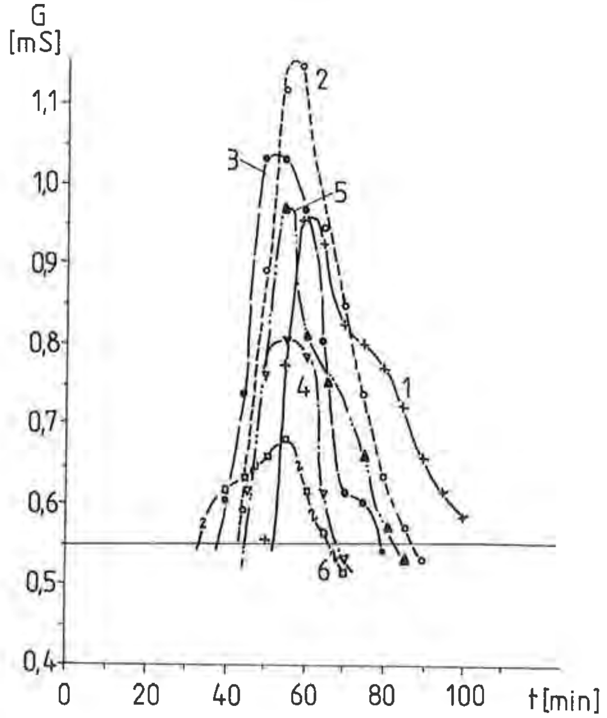

Fig. 1: Breakthrough curves of chloride ions in the sandy model.
Durchgangskurven von Chloridionen im Sandmodell.

This moment should be taken in account, especially, when the solution is poured into bore holes.

Radioactive nuclides used for tracing tests, for example, iodine-131, bromine-82, caesium-134, chrome-51-EDTA, sodium-24, rubidium-86, and others have certain advantages against classic tracers: low initial doses, quick and simple detection in situ, a low perception limit. A broader application of these tracers is, however, limited by sanitary regulations.

Tritium can be used as artificial tracer, as it meets most of criteria for the tracer selection and combines with a molecule of water (HTO, T_2O). From the hydrogeological point of view, the application of artificial tritium may contaminate the groundwater in hydrogeological structures which contain also very low activities of natural tritium from precipitation waters. The two different origins of this radionuclide cannot be distinguished in the measurement of samples. In such a case, the studies of the retention time of the groundwater in hydrogeological structures or regions are quite limited (S. Mareš & J. Šilar, 1978). From natural nuclides, helium-4 can be applied as an artificial tracer (G. J. Eikenberg et al., 1992).

The selection of a suitable tracer will represent a very important preparation phase for a positive result of the test, if many different factores are evaluated: structural, lithological, petrographical and hydrogeological conditions of the water-bearing collector, physical and chemical properties of the environment, and assumed duration of the test. Parametric measurements of sorption of the rock and soil sorption accompany the selection processes. Up to a principle, only the water from the area,

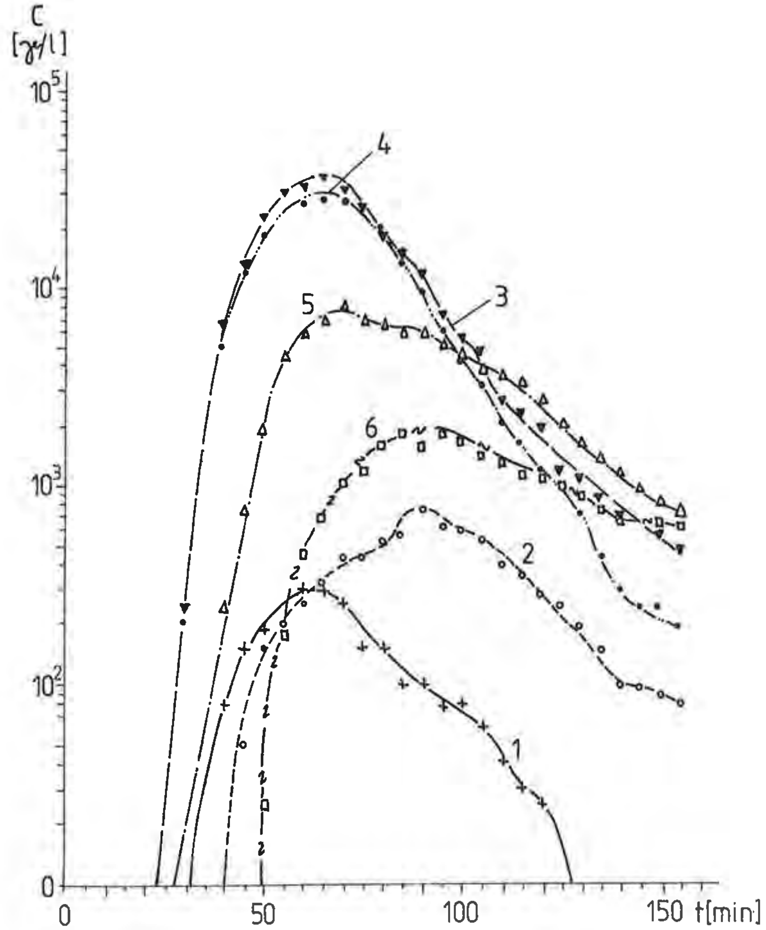

Fig. 2: Breakthrough curves of fluoresceine in the sandy model.
Durchgangskurven von Fluoreszein im Sandmodell.

where the test will be realized, should be used for laboratory tests. During tests in natural conditions, a part of the tracer is lost by hydrodynamic dispersion, sorption, and diffusion. According to practical experience, the effect of diffusion may be neglected (J. HANZLÍK, 1973). However, the other two processes may effect the measurement results quite substantially. If the movement of groundwater is measured between two points at a distance of 5 m, the final test result is affected by the structure, petrography and lithology of the water-bearing environment (J. HANZLÍK, 1973). The success of the measurement of the flow rate of groundwater by a tracer also depends on the uniform tagging of the water-bearing collector by the selected substance. Prior to the test, the hydrophysical properties of the rocks of the layers (strata) must be evaluated and the flow conditions within the bore hole should be assessed by measurement of the vertical flow rate (J. HULLA, 1989). The chosen section is delimitated in the bore hole profile by packers in order to secure the direct transition of the tracer into the water-bearing environment. The effect of the unmodified bore hole for a tracer tagging in the course of flow-rate measurements is illustrated in fig. 3.

The bore hole was not packed at the base of the water-bearing collector and the nitrite solution dropped to the bottom by its own weight. The subsequent tagging of water in the hole by ammonium salt solution limited the transfer of the first tracer into the collector although a sufficient hydraulic gradient has been formed. Changes of nitrite ion concentration are considerably delayed due to its slow washing-out and dilution.

The observation of the concentration decrease of the tracer in the infusion hole constitutes an inseparable part of the course of the tracer test. The results of these measurements enable us to determine the effective porosity of the permeable environment (J. HANZLÍK, 1974). It is reasonable (for time-saving reasons) to effectuate the flow-rate measurements of groundwater by tracers as a part of hydrodynamical tests even at small distances. The stationary pumping of water is

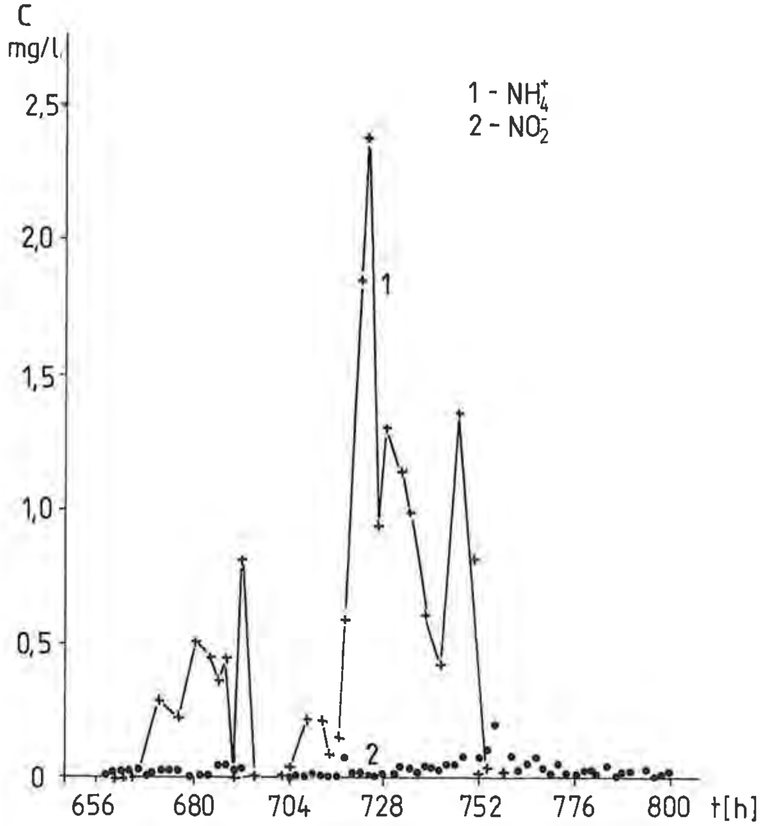

Fig. 3: Breakthrough curves of the tracer experiment with two tracers at the observation (pumping) well; fine-grained sandy aquifer, distance 48.5 m, depth below surface 25–40 m, Holešice (NW Bohemia).

Durchgangskurven des Tracerexperiments mit zwei Markierungsstoffen am Beobachtungsbrunnen; feinkörniger, sandiger Grundwasserleiter, Abstand 48,5 m, Tiefe 25–40 m, Holešice (NW Böhmen).

a necessary condition. In a pumping (observation) well, the pump is situated at the base of the observed collector. Experiments with tracers on a sandy model proved that the advance of tracer occurs in the lower part of the water-bearing collector (J. HANZLÍK, 1973). Pumping of water from the upper part of this layer is connected with a certain delay of the tracer within the observation well and with its additional dilution.

3. Discussion

The passage of the tracer at the observation site (bore hole, spring) is observed according to changes of its concentration (activity) in dependence of time. The breakthrough curve of the tracer in an isotropic, homologous, permeable environment acquires the shape of an asymmetric curve with an outstanding peak. The time coordinate of this peak determines the value of t_{max} for the calculation of the mean translational flow rate, which indicates the velocity of the movement of the groundwater on the connecting line between two points. From the viewpoint of the flow geometry, the existing anisotropy and inhomogenity of the environment, such a velocity represents the effect of the primary porosity of the water-bearing collector environment, i. e. the interconnection of most permeable pore channels between two points.

The curves resulting from the investigation of a tracer passage in natural conditions, do not usually have a smooth character. Considerable changes established during the tracer detection reflect the heterogenity of the water-bearing environment, which depends on the petrology of rocks and structural conditions. The course of the changes in tracer findings at the observation site enable the conception of flow conditions resp. flow geometry within the observed section to be rendered more truthfully (J. H. BLACK, 1989).

Examples of steady flow are illustrated for media with different permeability in fig. 4, 5. The breakthrough curves of tracers are marked by a continuous and quick increase of concentration up to the outstanding maximum. After the peak of the curve, in its right part, a quick concentration drop takes place. This course of the tracer occurrence at the observation site reflects the flow conditions within the pore-channel system as well as the distribution of the tracer concentration within the dispersion cone (N. N. PAVLOVSKIJ, 1956, H. SCHOELLER, 1962). The course and shape of the breakthrough curves indicate that the investigated water-bearing collectors can be qualified as a quasi-homogeneous and isotropic environment, from the viewpoint of the water flow.

The effect of rock fracturing on the water flow is demonstrated in fig. 6. The fracture systems in the directions SW–NE and NNW–SSE create the main flow paths due to their drainage function within the porous medium of sandstones. The course of the alteration of flow rates of tracers is characterized by outstanding peaks on breakthrough curves.

Curve 1 declares the tracer findings in water pumped from the well. Line 2 reflects the trace concentration changes in a spring, which is located on the line connecting the puring-in hole and the observation (pumping) well. The groundwater flow in Cenomanian strata measurements is independent of the hydrological conditions in the Novohradka river valley.

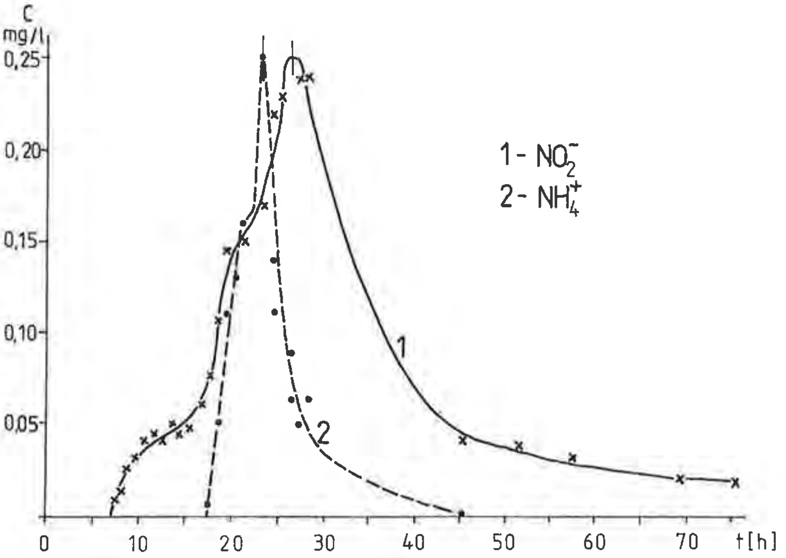

Fig. 4: Breakthrough curves demonstrating a uniform flow within the porous aquifer; coarse-grained sand and gravel, distance 15 m, depth of filter 7–9 m, Mělník, Labe river valley.
Durchgangskurven, die eine gleichförmige Strömung im porösen Grundwasserleiter zeigen; grobkörniger Sand und Kies, Abstand 15 m, Filtertiefe 7–9 m, Mělník, Labe Flußniederung.

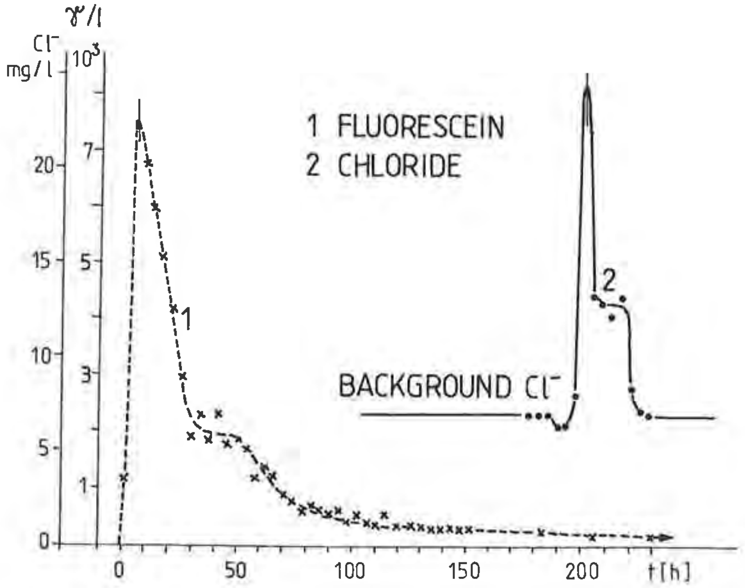

Fig. 5: Breakthrough curves demonstrating a uniform flow within a fissured aquifer; regularly fractured gneiss, distance 1–11 m, 2–32 m, depth of the opened part of bore holes 3–18 m, dam site, Horka, Krušné hory mountains, NW Bohemia.
Durchgangskurven, die eine gleichförmige Strömung in einem zerklüfteten Grundwasserleiter zeigen; gleichmäßig zerklüfteter Gneis, Abstand 1–11 m, 2–32 m, Tiefe des offenen Teils der Bohrstellen 3–18 m, Talsperre, Horka, Krušné Hory Berge, NW Böhmen.

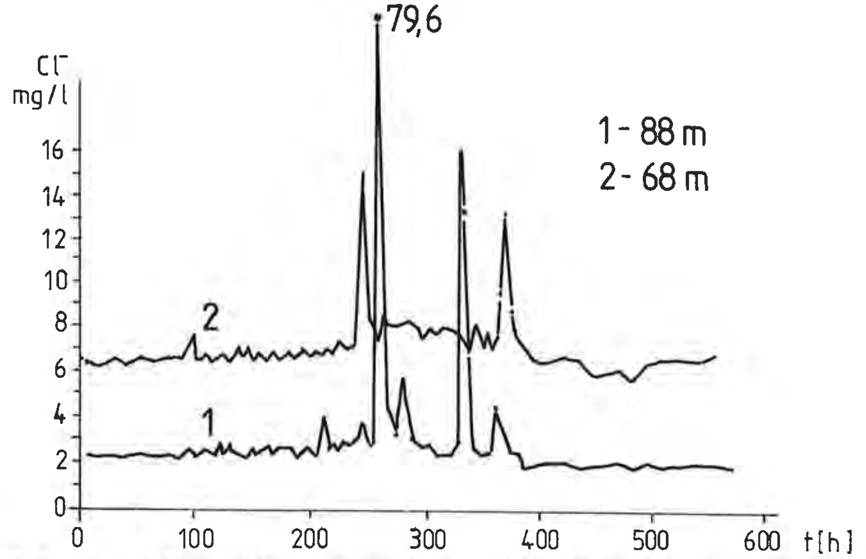

Fig. 6: Breakthrough curves demonstrating the flow within a fissured-porous aquifer; coarse and medium-grained sandstones – Cenomanian, distance 1–88 m (well), 2–68 m (spring), depth 46–78 m below surface, Luže, Novohradka river valley, E Bohemia.
Durchgangskurven, welche die Strömung in einem zerklüfteten, porösen Grundwasserleiter zeigen; grober und mittelgrober Sandstein – Cenoman, Abstand 1–88 m (Brunnen), 2–68 m (Quelle), Tiefe 46–78 m unter der Oberfläche, Luže, Novohradka Flußniederung, E Böhmen.

Rapid and expressive concentration changes of tracers in the observation point characterize the irregular water flow in the water-bearing collector. The water motion is affected by irregular development and alternation of lithologically different strata and the different permeability. The water flow is realized as successive overflowing, retardation and acceleration in dependence of the connection with permeable surfaces, adsorption, and desorption (Figs. 7, 8, 9; J. HANZLÍK, 1973).

In fig. 7 and 8, a certain effect of the failure of the collectors can be detected. The comparison between these curves and the curves in fig. 6 reveals that the low-permeable positions within the collector profile exert the decisive effect on the water flow process. The transfer of the tracer was also found in a quick-sand collector at the distance of 885 m after 493 hours between a bore hole from the surface and drainage well in the mine. The experiment proved the formation of privileged pathways within the collector due to the effects of drainage wells. The course of the concentration changes of the tracer (NO_2^-) could be evaluated quantitatively.

The determination of the time coordinate of the passage of a tracer at the observation site (t_{max}) at non-uniform flow is a certain problem. In such cases, the passage curve is without initial manifestations of the tracer (Fig. 7, 8). Frequently, this plane is not confined in the descending part of the curve due to the long washing-up of the tracer immobilized by sorption (tailing effect) (Fig. 7). During the tracing test the quantity of the tracer retained at the observation site is checked, too. These values should be verified by repeated tests as the mutual positions of sites must not necessarily agree with the prevailing flow direction of the groundwater in the observed section (J. HANZLÍK, 1973, T. HIMMELSBACH et al., 1992).

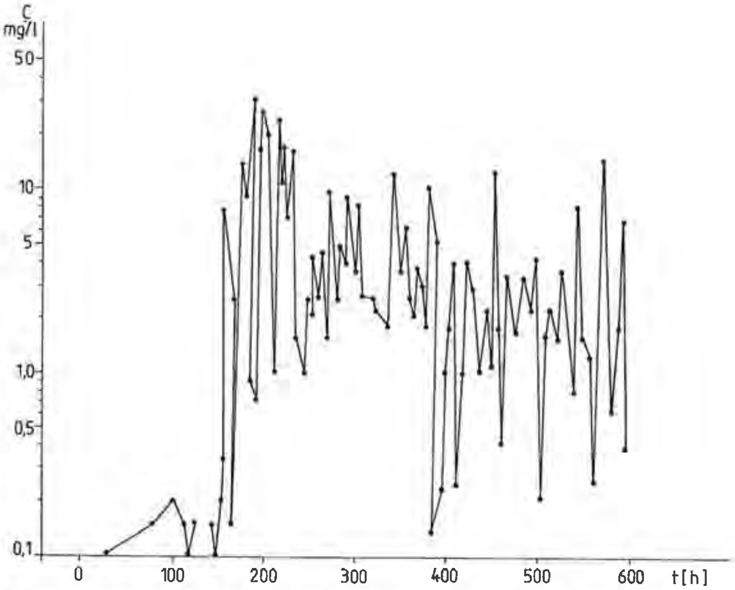

Fig. 7: Breakthrough curve of the nitrite ion demonstrating an irregular flow; fine-grained clayey sandstone (quick sand) – Miocene, distance 60 m (two wells), depth 159–179 m below surface, mining claim of Kohinoor mine, NW Bohemia.
Durchgangskurven von Nitritionen, die eine ungleichmäßige Strömung zeigen; feinkörniger, toniger Sandstein (Fließsand) – Miozän, Abstand 60 m (zwei Brunnen), Tiefe 159–179 m unter der Oberfläche, Claim der Kohinoor Mine, NW Böhmen.

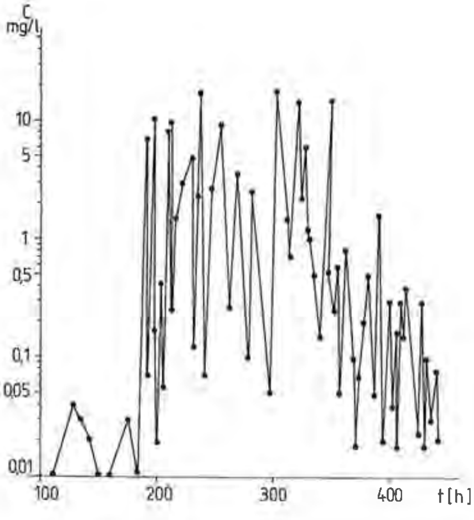

Fig. 8: Breakthrough curve of the nitrite ion demonstrating an irregular flow; fine-grained clayey sandstone (quick sand) – Miozän, distance 85 m (two wells), depth 150 m below surface, Mariánské Radčice coal basin, NW Bohemia.
Durchgangskurven von Nitritionen die eine ungleichmäßige Strömung zeigen; feinkörniger toniger Sandstein (Fließsand) – Miozän, Abstand 85 m (zwei Brunnen), Tiefe 150 m unter der Oberfläche, Mariánské Radčice, Kohlenrevier, NW Böhmen.

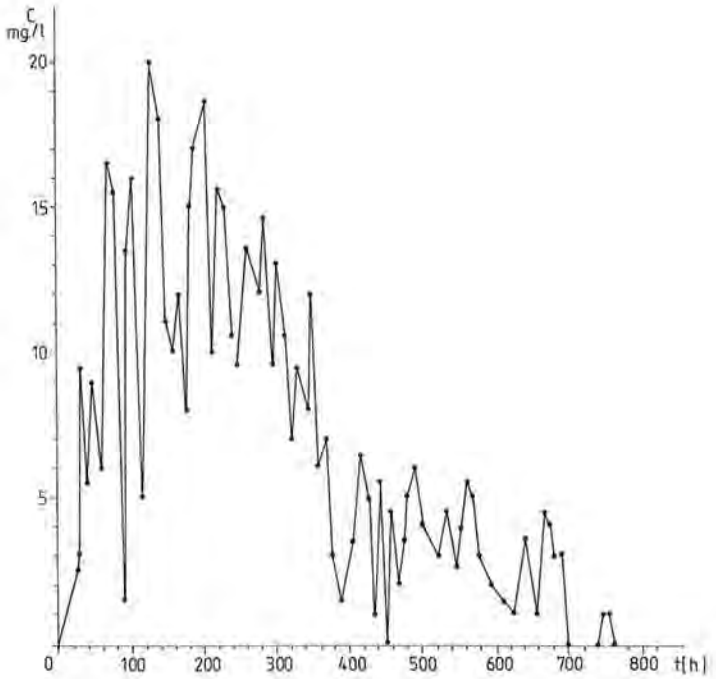

Fig. 9: Breakthrough curve of the nitrite ion demonstrating an irregular flow; sandy clayey strata series with thin coal seams – Miocene, distance 20 m (two wells), depth of filter 11–14 m, Vysočany fly-ash setting pit, NW Bohemia.
Durchgangskurven von Nitritionen die eine ungleichmäßige Strömung zeigen; sandige, tonige Schichtenfolge mit dünnen Kohlenflözen – Miozän, Abstand 20 m (zwei Brunnen), Filtertiefe 11–14 m, Vysočany – mit Flugasche gefüllte Grube, NW Böhmen.

Summary

For achieving positive results, the tracer test carried through by the distance method will require detailed preparation as far as time and financial requirements are concerned. However, the results of tracing tests enable the groundwater flow to be quantified and information about flow conditions in a water-bearing collector or system to be completed. An important contribution of the tracer test is connected with the evaluation of the effect of fissures on flow conditions in the water-bearing collector. Such information is very important for activating protective measures for the aquifer against contaminants and negative effects of waste heaps.

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Zusammenfassung

Die Festsetzung der Grundwasserbewegung in den wasserführenden Systemen in Zeit und Raum gibt eine bedeutende Information für die Quantifizierung des hydrogeologischen Regimes im untersuchten Gebiet. Eine der Methoden ist die Anwendung natürlicher und künstlicher Tracer für die Bestimmung der Zusammenhänge, der Richtungen und Geschwindigkeiten des Grundwassers. Tracermethoden werden in größerem Maße mit den wachsenden Bedürfnissen des Grundwasserschutzes eingesetzt.

Die Beschreibung künstlicher Tracermethoden inkludiert die Bewertung der Grundwasserbewegung in Abhängigkeit von der geologischen Struktur und den petrographischen Verhältnissen. Die präzise Festsetzung der mittleren Verweilzeit des Tracers im Untergrund hängt nicht zuletzt von den hydrogeologischen Bedingungen während des Versuches und daraus ableitend von seiner Konzentrationsveränderung bei seinem Austritt ab. Wichtige Bestandteile jedes Tracerversuches sind die Auswahl geeigneter Markierungsstoffe und der Einspeisungsstollen, die Probenentnahme und Analytik. Die Ergebnisse von Tracerversuchen in Grundwasserleitern mit verschiedener petrographischer Zusammensetzung und tektonischer Beanspruchung sind nur kurz beschrieben. Als wesentlicher Beitrag des Tracerversuches für die Erfassung der Grundwasserdynamik sind Informationen über den Einfluß der Klüfte anzusehen.