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Use of Tracer Tests and Geophysical Logging to Understand Solute and Micro-organism Tracer Responses in Monitoring Wells with Long Screen Intervals in a Gravel Aquifer.

Zum Verständnis des Transports von löslichen Stoffen und Mikroorganismen an durchgängig verfilterten Grundwassermessstellen in einem Kiesaquifer mittels Markierungsversuchen und Wärmeflussmessungen

R. Flynn[1]), Y. Hacini[2]), P.-A. Schnegg[3]), R. Costa[4]) & K. A. Diomande[5])

Content

[1]) Dr. Raymond Flynn, School of Planning, Architecture and Civil Engineering, Queens University Belfast, Stranmillis Road, Belfast BT9 5AG. Northern Ireland. E-Mail: r.flynn@qub.ac.uk

[2]) Youcef Hacini, Geophysical Institute, University of Lausanne, CH-1015 Lausanne, Switzerland. E-Mail: Youcef.Hacini@ig.unil.ch

[3]) Dr. Pierre-André Schnegg, Geomagnetism Group, University of Neuchâtel, Emile Argand 11, CH-2007 Neuchâtel, Switzerland. E-Mail: pierre.schnegg@unine.ch

[4]) Roberto Costa, Geomagnetism Group, University of Neuchâtel, Emile Argand 11, CH-2007 Neuchâtel, Switzerland. E-Mail: roberto.costa@unine.ch

[5]) Karim Abdoul Diomande, Hydrogeology Centre, University of Neuchâtel, Emile Argand 11, CH-2007 Neuchâtel, Switzerland. E-mail: karim.diomande@unine.ch

1. Introduction

Drinking water quality plays a significant role in infectious disease transmission. Despite recent studies suggesting that the role of microbiological contaminants in drinking water play in causing waterborne disease may have been exaggerated (P. K. Jensen et al., 2004), there can be little doubt that the presence of pathogenic micro organisms significantly influences the suitability of groundwater for human consumption. In both developed and developing countries, micro-organisms such as viruses, bacteria, and protozoa have been recognised as a major contaminants of concern, that may cause both short-term (acute) and long-term (chronic) illness. This may lead to death, particularly among very young, elderly and immuno-compromised individuals (World Health Organisation, 2003). The threat to groundwater quality from micro-organisms is particularly acute for karstic (D. G. Boyer & G. C. Pasquarell, 1999) and coarse gravel aquifers (T. Ginn et al., 2002).

The United States Environmental Protection Agency (1992) has proposed a series of regulations known as the "Groundwater Rule", which are designed to reduce the public health risk resulting from consumption of groundwater impacted by pathogens (B. Macler, 1996). Moreover, similar legislation has been under consideration in some European countries (J. F. Schijven & S. M. Hassanizadeh, 2000). The groundwater rule recognises that the capacity of aquifers to remove introduced micro-organisms from groundwater may not be perfect. Moreover removal of micro-organisms by the aquifer, often called the groundwater disinfection capacity, may vary from one deposit to another, being strongly dependant on features such as aquifer mineralogy and texture (R. Flynn et al., 2004a). To date, no systematic means of assessing groundwater disinfection capacity exists. Indeed, the authors B. Macler & J. C. Merkle (2000) recognised the importance of further research into mass transport and attenuation processes, if the means by which micro-organisms are removed by aquifers are to be better understood. A better understanding of these processes would in turn provide an indication of the vulnerability of groundwater sources exploiting various types of aquifers to contamination by pathogenic micro organisms.

Tracer testing using conservative tracers offers a useful means of determining mass transport parameters, and can be particularly useful for in-situ studies in highly heterogeneous deposits, where conventional rules of thumb, widely applied to more uniform aquifers, may not apply. Similarly, the complimentary use of micro-organisms as tracers permits contaminant-specific microbial attenuation processes to be identified and groundwater disinfection capacity to be more confidently evaluated.

W. Käss (1998) notes that conservative tracers can provide important information about in-situ mass transport processes, such as advection and dispersion, which may be difficult or even impossible to determine using other hydrogeological techniques. The author provides a detailed description of the benefits and drawbacks of a range substances widely used as conservative tracers in groundwater. Similarly R. Kretzschmar et al. (1999) summarise the processes controlling the transport of colloidal particles, including micro-organisms, in aquifers. More detailed descriptions of processes affecting bacteria and protozoa are described in T. Ginn et al. (2003), while J. F. Schijven & S. M. Hassanizadeh (2000) summarise the processes controlling virus transport and the use of bacteriophage (bacterial viruses) as microbiological tracers. Moreover, P. Rossi et al. (1999) demonstrated that bacteriophage may be used in both karstic and porous media environments where groundwater may be vulnerable to contamination by pathogenic micro-organisms.

Despite the benefits derived from tracer testing, the technique remains largely underutilised as a means of investigating contaminant transport and groundwater vulnerability. This is to some degree, due to the significant financial outlay necessary for site instrumentation. Sites, such as the United States Geological Survey (USGS) test site at Cape Cod, USA employ multilevel samplers that permit solute and microbiological tracer breakthrough curves to be generated from samples collected over thin depth intervals (e.g. R. W. Harvey & S. Garabedian, 1991). However, installation of these multi-level sampling systems tends to be more costly than that of conventional monitoring wells. Moreover, the design of such systems often remains a compromise between depth resolution and the number of sampling points that need to be installed. Indeed, since parts of the saturated thickness are occupied by well completion materials, such as bentonite plugs that provide hydraulic isolation, multiple level systems, such as single hole piezometer nests, cannot sample the entire saturated thickness of an aquifer. It is thus possible that those zones transporting tracer may not be sampled (R. M. Flynn et al., 2004b). Finally, the presence of large numbers of sampling points may present the hydrogeologist with the dilemma, when analytical capabilities are limited, namely whether many samples should be collected from selected sampling points or should all monitoring points be sampled, but less frequently.

Boreholes and monitoring wells with long screened intervals are often more cheaply installed than multilevel samplers and offer an alternative means of monitoring groundwater for tracer content. However, one of the principal drawbacks of collecting whole-well samples using long-screened wells/boreholes is their lack of vertical resolution when identifying the elevation of unit supplying tracer to a well. Studies such as those completed by M. Schirmer et al. (1995) and D. Lerner & I. Jones (1995) have further investigated this issue, and the possibility of employing alternative sampling technologies in wells/boreholes with large exposed intervals to obtain groundwater samples that are more representative of immediately adjacent horizons. However, both groups of authors noted the limited benefit of using these approaches in wells screened in unconsolidated deposits where the gravel pack surrounding the well screen cannot be hydraulically isolated. This results water being sampled from horizons that are non-adjacent to the level being pumped. Moreover, this situation is often made worse by vertical flow in the well/gravel pack which may actively transport water from horizons not immediately adjacent to the sampling point resulting in samples that may be more representative of non-adjacent units. Indeed, in order to fully understand the origin of the water obtained at a sampling point in a long-screened well, the well water flow regime must be characterised; geophysical logging methods such as heat pulse flowmeter measurements provide a useful means of achieving this goal (D. Chapellier et al., 2000).

This paper describes a series of comparative tracer tests carried out using solute and microbiological tracers in a highly permeable peri-alpine fluvioglacial sand and gravel aquifer. These deposits fall into a category of aquifers considered as sensitive to microbiological contamination (United States Environmental Protection Agency, 1992). Groundwater monitoring for tracer content carried out in a well with 3 m long screened interval, 20 m down-gradient of the tracer injection point permitted the response of both tracers with depth to be evaluated. The results of comparative test were further evaluated using a heat-flow geophysical logging tool and a recently-developed mobile downhole fluorometer. Test results were evaluated both in terms of their significance for tracer test interpretation, and in terms of groundwater vulnerability assessment.

2. Site Setting

This study was carried out at the Kappelen Test Site (Kappelen), Canton Berne, Switzerland (Fig. 1). The site is instrumented with seven five inch (125 mm) inner diameter shallow wells screened at between approximately 5 m and 8 m below ground surface (m BGS) and nine deep wells of the same diameter screened between 10 m BGS to 16 m BGS. K. Kennedy et al. (2001) provide further details of well construction at the site. The two shallow wells, the injection well K1-2 and the observation well K3-2, 20 m downgradient, form the focus of this study.

Geological logging of cores taken at selected drilling locations associated with monitoring well installation at Kappelen indicated that the site is underlain by heterogeneous coarse to fine gravels with occasional sand layers. These deposits form part of the regionally important Seeland fluvioglacial gravel aquifer (P. Kellerhals & B. Trohler, 1976). Detailed logging at K3-2 and associated granulometric analysis of representative

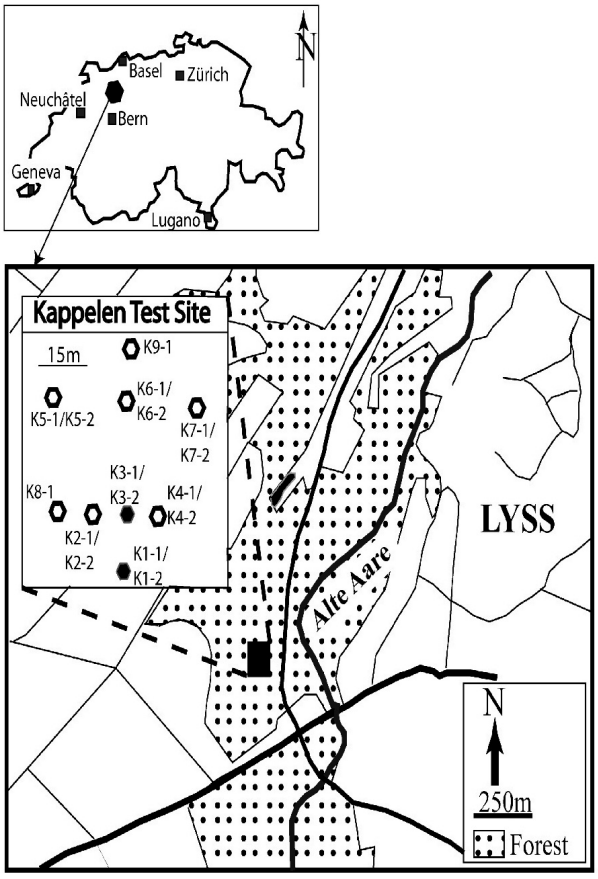

Fig. 1: Location map of Kappelen Test Site. Inlay: Detaisl of test site with well location. Injection well, K1-2 and observation well, K3-2 in black.
Standort Kappelen mit Detailansicht des Testgebietes und Lage der Grundwassermessstellen. Eingabebrunnen (K1-2) und verwendete Messstelle (K3-2) in Schwarz.

samples (Fig. 2) indicated that the hydraulic conductivity of the deposits screened against the K3-2 varied between 3 and 1187 m/day, although the majority of the hydraulic conductivities calculated approached the upper end of this range. These data suggested that different breakthrough curves could be anticipated at different depths during tracer testing using the site's observation wells.

3. Materials and Methods

Tracer testing employed solute and microbiological tracers to investigate mass transport processes in the deposits underlying Kappelen. Uranine (Sodium Fluorescein) acted as the solute tracer for all experiments. W. Käss (1998) summarised the results of field studies using uranine and noted that where appreciable quantities of organic matter are absent, as is the case with the Kappelen Aquifer (< 0.1 % by weight C_{org}), the compound is believed to undergo little to no interaction with aquifer materials.

The bacteriophage, H40/1 acted as the microbiological tracer during comparative tracer testing. H40/1 is a marine bacteriophage naturally absent from freshwater systems, including aquifers. The phage has considerable advantages as a tracer, most notably, that it is non-pathogenic, inexpensively cultivated to high concentrations (up to 10^{11} plaque forming units per millilitre (pfu/mL)) while easily detected at concentrations as low as 1 pfu/mL. P. Rossi (1994) provides more detailed information on the use of bacteriophage, including H40/1, as groundwater tracers. Bacteriophage assays

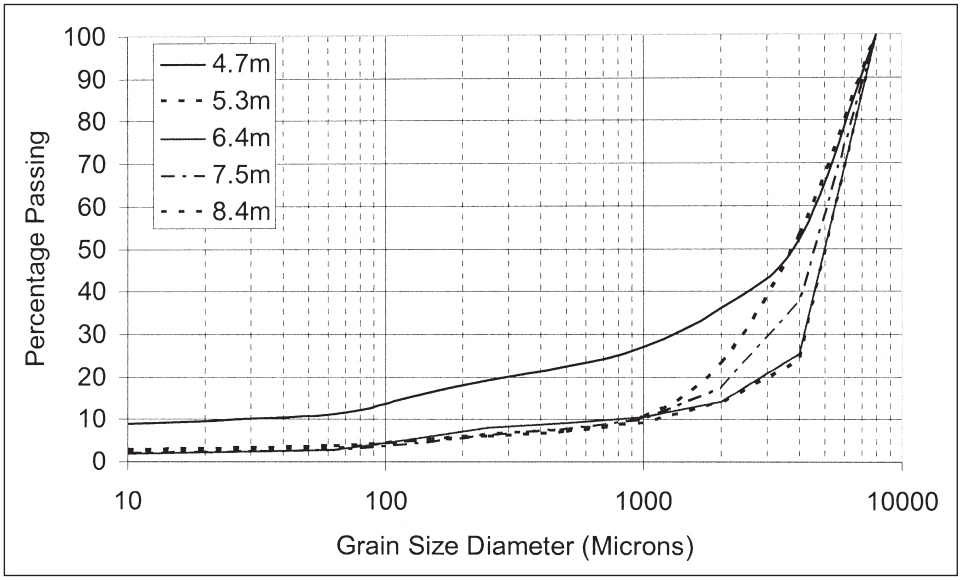

Fig. 2: Representative grain size distribution analyses for samples of aquifer material collected from depth corresponding to the screened interval of K3-2, Kappelen, Switzerland. Hydraulic conductivity estimated from Hazen rule (R. A. Freeze & J. A. Cherry, 1979).
Repräsentative Korngößenverteilungskurven für Aquifermaterial aus verschiedenen Tiefen entsprechend der Filterstrecke von K3-2, Kappelen, Schweiz. Hydraulische Leitfähigkeit abgeschätzt nach der Hazen-Regel (R. A. Freeze & J. A. Cherry, 1979).

of groundwater samples were completed using the procedure described in R. M. Flynn et al. (2004a).

Three field-based tracer tests were carried out in the framework of this study. The tests were carried out in mid to late July over three consecutive years from 2000 through 2002.

3.1. Test 1

An initial tracer test was carried out to ascertain whether a previous test carried out by K. Kennedy et al. (2001) could be reproduced. The tracer cocktail of 75 g of uranine and 3×10^{14} pfu of H40/1 were injected over a 15 min period into a continuously circulating system installed in K1-2, which pumped groundwater from the base of the well to the surface where low volumes of concentrated tracer were added before the solution was reinjected at the top of the well screen. The system had the advantage of permitting the injected tracer to enter the aquifer under natural gradient conditions, thus avoiding localised temporary hydraulic disturbances to the groundwater flow field during injection. Following injection, the tracer was circulated for a further 12 hours, while a University of Neuchâtel Geomagnetism Group (GGUN) field fluorometer measured concentrations in water at wellhead at 4 min intervals until the end of circulation. Further details of the GGUN fluorometers operation are contained in P. Schnegg & F. Bossy (2001). A similar on-line circulation system was employed at K3-2, where solute concentrations were monitored on-line and aliquots of circulating water were collected for bacteriophage analysis using the system presented in Fig. 3, until the end of the test 150 hours later. Bacteriophage samples were assayed within 24 hours of collection. Comparison of solute and bacteriophage tracer concentrations with concentrations in aliquots of the source material injected in K1-2 permitted dimensionless relative concentrations of both tracers to be ascertained and compared to one another.

3.2. Test 2

The objective of Test 2 was to evaluate if, as granulometric analyses suggested, tracer response in K3-2 would vary with depth, due to variability in hydraulic conductivity. The injection procedure involved adding 10 g of uranine and 1.9×10^{14} pfu of H40/1 to circulating well water in K1-2 in the manner used during Test 1. In order to ascertain the variability of tracer response with depth in the observation well, samples were collected continuously from five approximately equally spaced intervals along the three metre well screen interval using a multi-channel peristaltic pump. The pump extracted groundwater from the well at a rate of 100 ± 20 ml/hour per channel. Groundwater from each level was collected by separate channels of a multi-channel automatic sampler at 1 hour intervals. The volume of water in each sample was used to correct test results for the time taken for water to travel from the sample point in the well to the sample container.

Drawdown induced by the sampling was less than the measurement error of the water-level meter (0.5 cm), and was believed to have a negligible influence on hydraulic gradients toward the well. As in Test 1, concentrations of solute and bacteriophage tracers were ascertained within 24 hours of sampling and compared to source concentrations.

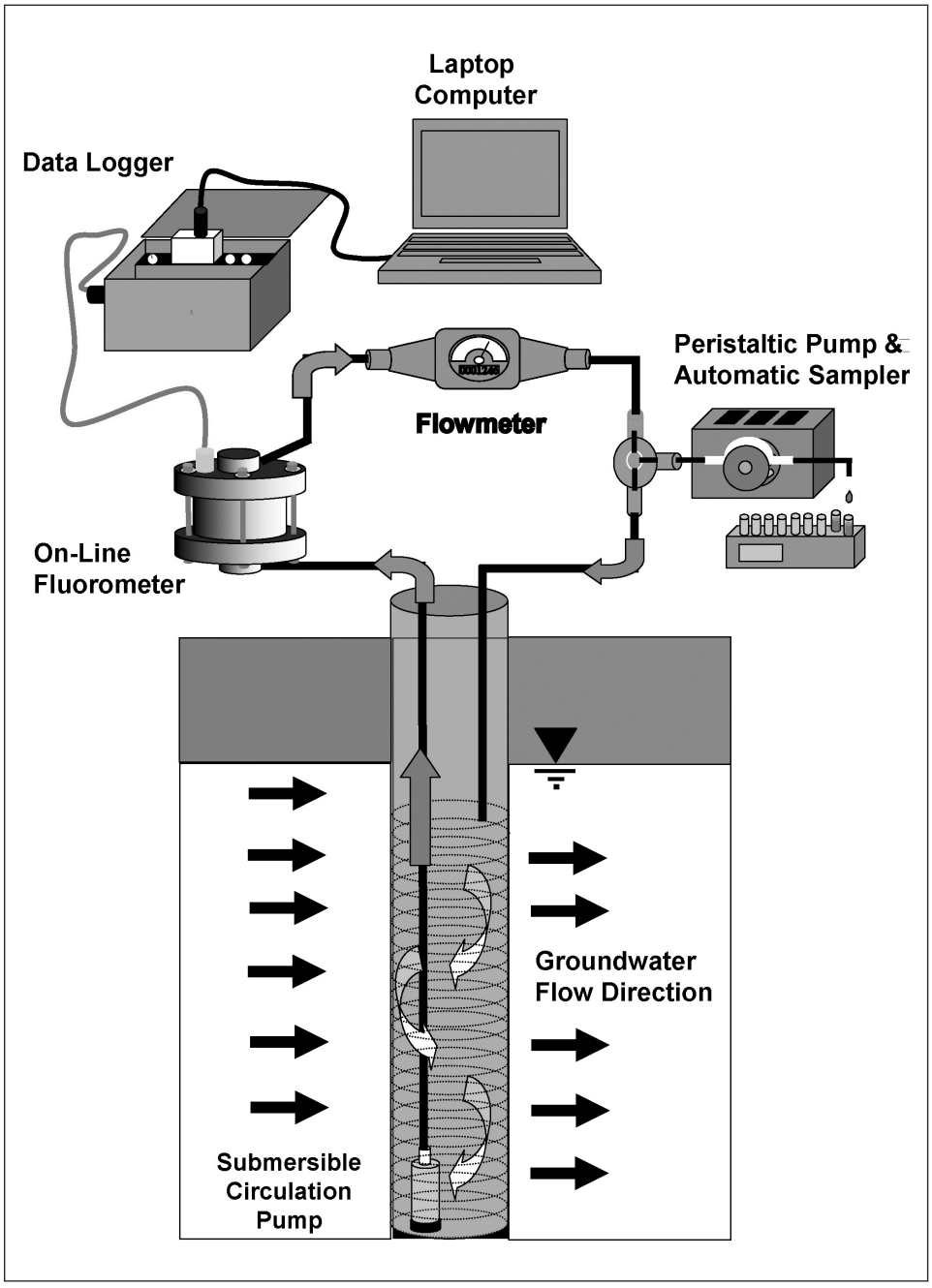

Fig. 3: Continuous circulation apparatus used to monitor tracer concentrations in injection well, K1-2 and observation well, K3-2. Note: Automatic sampler not used in injection well setup.
Apparatur mit kontinuierlichem Durchfluss zur Analyse der Tracerkonzentrationen im Eingabebrunnen (K1-2) und in der Messstelle (K3-2). Anmerkung: Automatischer Probenehmer nur für die Messstelle.

3.3. Test 3

The third test carried out in the framework of this study measured the temporal variation in solute tracer response with depth in more detail using a mobile downhole fluorometer. Injection of 150 g of uranine mixed with 20 l of K1-2 well water followed the procedure used in Test 1. The higher concentrations of uranine were employed in this test permitted horizons where low levels of tracer may arrive to be detected. A more detailed description of the fluorometers operation is provided in R. M. Flynn et al. (2004c). The fluorometer measured the variation in tracer concentration in 5 cm increments in the water column of K3-2 at 12 hour intervals. Prior to Test 3, single well dilution tests, in which a pulse of tracer was injected into the water column and then subsequently diluted by natural groundwater flow, demonstrated that all detectable levels of tracer in the observation wells screened interval were removed one hour after injection.

Complimentary heat flow logging carried out using Mount Sopris HFP-2293 heat pulse flow meter determined the magnitude and direction of water flow in K3-2. Qualitative measurements, completed two weeks prior to Test 2, indicated the direction of flow in the well. Subsequent quantitative measurements carried out within one month of Test 3 provided additional insight into the hole's hydraulic regime. During this second phase of measurements the flow meter measured vertical flow rate and direction in triplicate at 50 cm depth intervals. These measurements were repeated six months

*Tab. 1: Summary table of results of Tests 1 through to 3, Kappelen Test Site, Switzerland. * – as determined from R. W. Harvey & S. Garabedian (1991), m BGS-metres below ground surface. C_o – calculated by dividing mass injected by injection well volume, N/A – not analysed – bacteriophage tracers not used in Test 3.*
*Ergebnisse der Markierungsversuche 1 bis 3, Testgebiet Kappelen, Schweiz. * – nach R. W. Harvey & S. Garabedian (1991), m BGS-Meter unter Geländeoberkante, C_o – errechnet aus Eingabemasse geteilt durch Volumen des Eingabebrunnens, N/A – nicht analysiert – Bakteriophagen in Test 3 nicht eingesetzt.*

	Uranine			H40/1 Bacteriophage			Relative Recovery (H40/1 /Uranine)*
Study	First Arrival (Hrs)	Peak Conc Time (Hrs)	Peak Relative Conc (C/C_o)	First Arrival (Hrs)	Peak Conc Time (Hrs)	Peak Relative Conc (C/C_o)	
Test 1 (whole well samples)	24.8	60.6	3.20E-04	19.16	30.83	1.48E-07	9.50E-05
Test 2 (sampled from 7.8 m BGS)	38	78	6.45E-05	25.5	35.5	7.11E-09	4.14E-05
Test 3 (Downhole Fluorometer)	29	70	7.20E-05	N/A	N/A	N/A	N/A
Kennedy et al. (2001)	13	83	1.00E-03	12	27	2.00E-06	1.00E-04

later in December 2002 to determine whether the magnitude or direction of flow varies seasonally.

4. Results

Table 1 summarises the results of tracer tests 1 through 3, and compares the results with to those obtained by K. KENNEDY et al. (2001). It is notable that although uranine peak concentration times differ, they occur within 24 hours of one another. The correspondence is between first arrival times, peak arrival times and maximum concentrations are greatest between Test 2 and Test 3.

The similarity in peak concentration times for bacteriophage responses varies by 7 hours between Test 1 and Test 2 and the experiments completed by K. KENNEDY et al. (2001). However, although maximum uranine relative concentrations vary by ap-

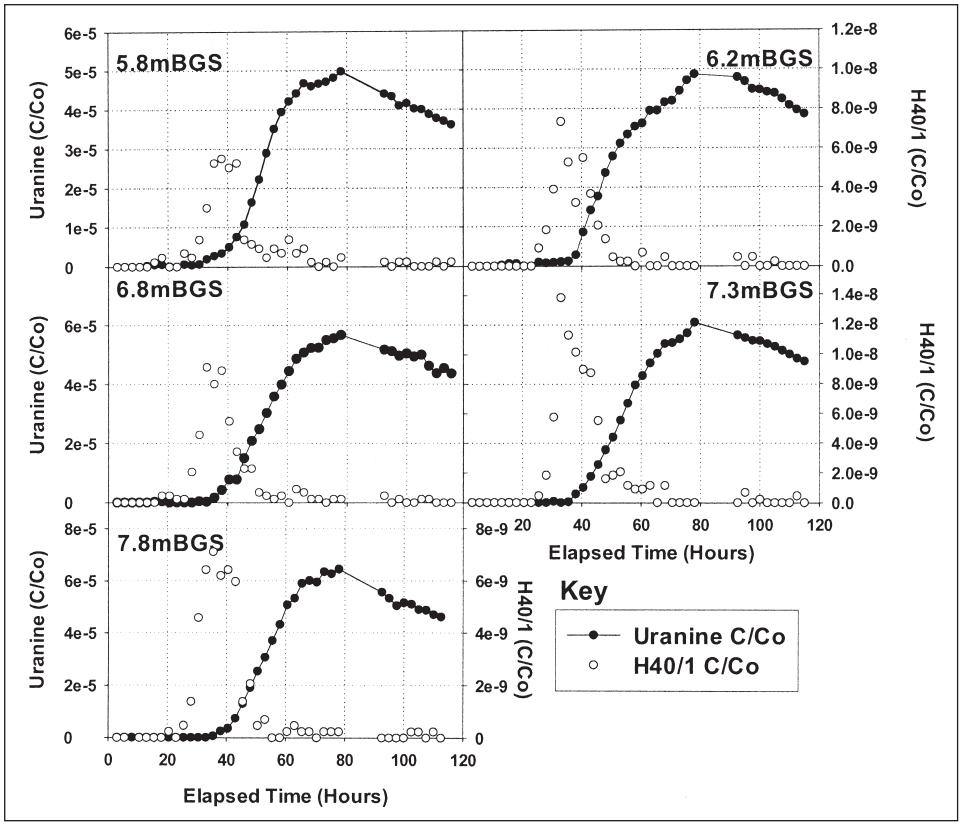

Fig. 4: Breakthrough curves for five different depths sampled using a multichannel low-flow sampling system at K3-2, Kappelen Test Site, Switzerland. C/C_o – injectate concentration, m BGS-metres below ground surface.
Durchgangskurven in fünf verschiedenen Tiefen ermittelt mit Hilfe eines Multi-level-Probenahmesystems an K3-2, Testgebiet Kappelen, Schweiz. C/C_o-Injektatkonzentration, m BGS-Meter unter Geländeoberkante.

proximately half an order of magnitude between tests, those for H40/1 vary by over two orders of magnitude.

Nonetheless, when relative recovery (R. W. Harvey et al., 1993) is considered, it is notable that the three tracing tests (Test 1, Test 2 and K. Kennedy et al., 2001) values vary by less than a factor of three.

Bacteriophage and uranine breakthrough curves generated from samples collected at five different depths in K3-2 during Test 2 are presented in Fig. 4. It is apparent that there is very little difference in either response time or relative concentrations between sampling depths, despite the differences in lithology observed in borehole cuttings which indicated variations in hydraulic conductivity, and thus anticipated variations in tracer response.

Figure 5 provides a temporal compilation of tracer profiles observed with depth in K3-2 over the duration of Test 3. The data show that, following breakthrough, tracer concentrations in K3-2 had a consistent profile for the rest of the test monitoring period. Tracer levels rise sharply in a 50 cm interval starting after 50 cm below the base of the well screen. Concentrations for the remaining deepest two metres of the wells screened interval remain constant.

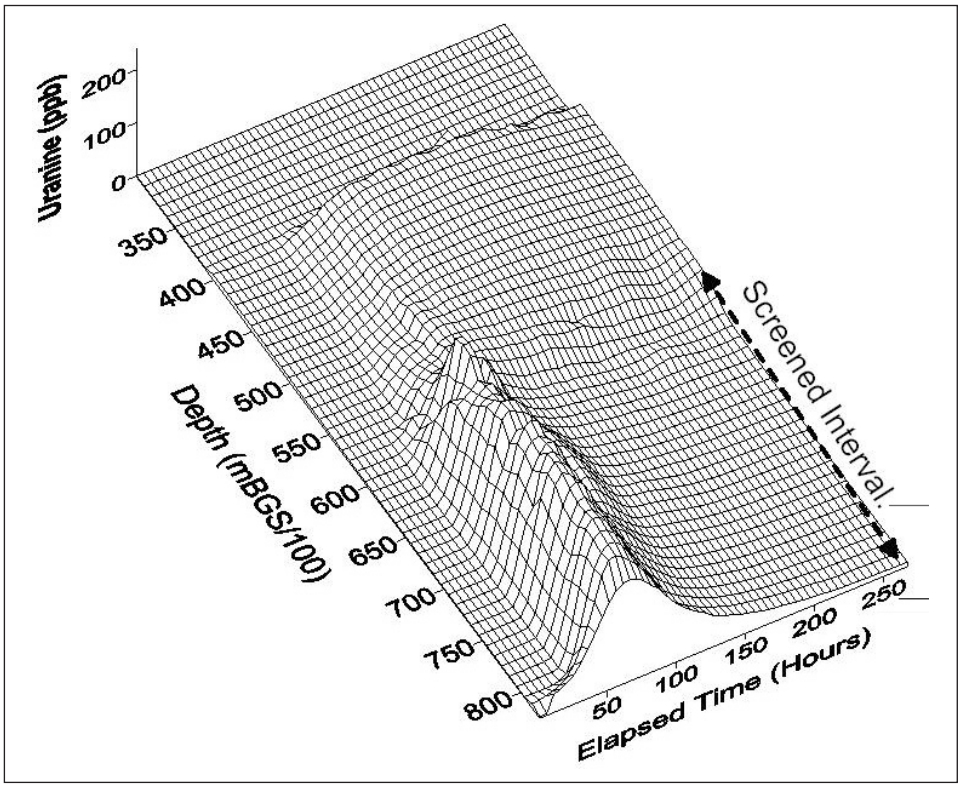

Fig. 5: Composite depth-specific breakthrough curve generated using mobile downhole fluorometer, K3-2, Kappelen, Switzerland. Note: Tracer storage above screened interval due to tracer displacement by fluorometer during successive measurement cycles.
Mittels eines mobilen in-situ-Fluorimeters generierte tiefenspezifische Durchgangskurve, K3-2, Kappelen, Schweiz. Anmerkung: Tracerkonzentrationen oberhalb des verfilterten Bereichs aufgrund von Verschleppung durch das Fluorimeter während der Messungen.

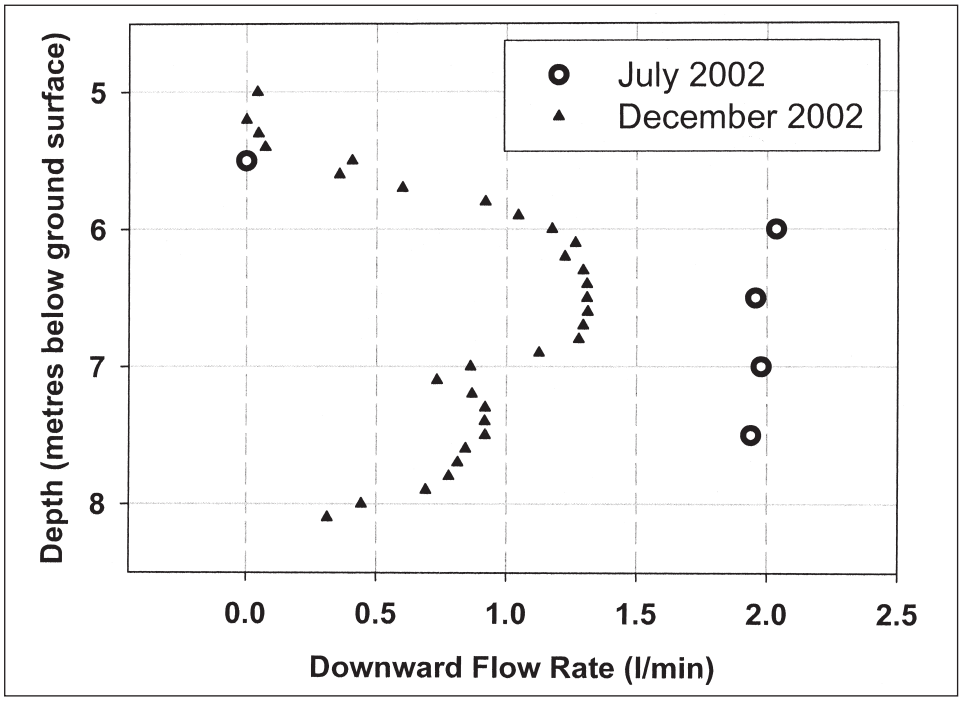

Fig. 6: Downward flow rates in K3-2, Kappelen, Switzerland, measured using heat pulse flow meter in July 2002 and December 2002.
Vertikal absteigender Wasserfluss mittels Wärmeflussmessung im Juli 2002 und Dezember 2002 an K3-2, Kappelen, Schweiz.

The July 2002 results for the heat pulse measurements, presented in fig. 6 indicate that vertical flow rates were not significant above 6.0 m BGS in K3-2s, but became important for the lower two metres of K3-2 screened interval. The increase in the flow rate in the 5.5 to 6.0 m BGS zone reflects the entrance of groundwater into the well over this interval. Flow below 6.0 m BGS was consistently downwards at a rate of between 1.9 and 2.0 l/min. These results are consistent with qualitative heat pulse flow meter measurements made the previous summer. Moreover, the results of more detailed measurements carried out in December 2002 indicate that although the vertical flow regime in the borehole differed from that carried out earlier in the year, water continued to enter the well at between 5.5 and 6.0 m BGS and subsequently flow downward on both occasions.

5. Interpretation

The results of Test 1 and Test 2 show that both the solute and bacteriophage tracers injected into K1-2 are carried by groundwater to K3-2 at similar rates to those observed by K. Kennedy et al. (2001), where a whole well sampling setup was also employed (Fig. 2). However, the difference in arrival times and peak concentrations suggests that the transport conditions between the experiments varied. It is nonetheless noteworthy that the flow velocities, based on peak solute concentration times, range from 6–8 m/day.

These values are considerably more than the 1 m/day rule of thumb widely assumed as mass transport rates in the Seeland Aquifer.

Similarly, bacteriophage arrival times and concentrations also varied between tests. However, despite these differences, bacteriophage relative recoveries vary significantly less. This indicates that variations in attenuation rates along flow paths connecting the injection well to K3-2 were less than those for mass transport rates.

The temporal variations in mass transport conditions contrast with the spatial variability of the solute and microbiological tracer breakthrough curves generated for different depths using groundwater samples collected at K3-2 during Test 2. These curves indicate a remarkable uniformity in both bacteriophage and solute response, although bacteriophage recovery is significantly lower reflecting attenuation processes. These uniform results were observed despite the results of granulometric analyses of samples collected at K3-2 from depths corresponding approximately to the observation wells screened interval which suggest that different responses would be anticipated for sampling points set at different intervals in the well.

The uniformity of the response in K3-2 during Test 2 may be partially explained by considering the uranine response observed during Test 3. Indeed, the results of Test 3, viewed in conjunction with heat pulse flow logging data indicate that uranine entered K3-2 during the test in the zone between 5.5 and 6.0 m BGS. Vertical flow conditions in the well resulted in the tracer flowing downwards toward the base of the well, with few additional groundwater contributions from other horizons in contact with the well screen. Upon reaching the base of the screened interval, the tracer left the well and re-entered the aquifer at a lower level in the aquifer.

Although, both tracer tests and heat flow logging indicate that hydrodynamic conditions may change in the Kappelen Aquifer from one tracer test to another, the response in the observation well during Test 2 is consistent with what would be anticipated in based on the results of Test 3. Indeed, the solute tracer responses in these two tests are more similar to one another than they are to those observed in Test 1 or the test carried out by K. Kennedy et al. (2001). Moreover, the results of heat flow logging, although indicating variations in flow rate, suggest that the conditions in K3-2 were similar during Test 2 and Test 3. These points suggest that the phenomena observed during Test 3 using the downhole fluorometer were operating during Test 2, when samples were collected with the multi-channel peristaltic pump. Furthermore, the similarity of bacteriophage responses at each depth during Test 2 is consistent with bacteriophage being transported to the well via the thin preferential flow zone that also transported the solute. Similarly, upon entering the well, the bacteriophage are believed to have been transported to the base of the wells screened interval, where they re-entered the aquifer. Finally, it is noteworthy that despite the availability of continuous borehole core at K3-2, the preferential flow zone identified in Test 3 could not be visually identified. This is partially believed to be a consequence of the hollow core barrel rotary percussion drilling technique employed which disturbs the structure of geological materials and mixes deposits from different horizons upon extrusion at the ground surface.

6. Conclusions

The tracer and geophysical logging techniques employed in tests 1 through 3 have emphasised a number of points which need to be considered when studying mass trans-

port processes in heterogeneous porous media. The results of all tracer tests showed that mass transport rates in the porous aquifer were considerably greater than those normally assumed, and provide a valuable contribution to the understanding mass transport processes in the Seeland Aquifer. These data are necessary if the vulnerability of groundwater supplies to contamination is to be adequately assessed. Nonetheless, the test results also highlight the fact that vertical and horizontal hydraulic gradients in the gravel aquifer may vary with time, and responses from a single test may not reflect mass transport conditions on other occasions. Indeed, the fact that all three tracer tests carried out in the framework of this investigation program were completed in summer time, when water levels were declining from their springtime high suggests that the variation in responses observed underestimates the true range of variability that may be observed during the hydrological year. This is corroborated by differences in vertical flow measurements carried out at K3-2 in summertime and wintertime. Despite these variations, the bacteriophage relative recovery data indicate that a lesser degree of variation is apparent in terms of the attenuation capacity of the aquifer material.

The test results demonstrate that investigations using tracers can provide important information that can considerably assist in developing groundwater protection zone strategies for groundwater sources, particularly in highly heterogeneous porous deposits. Nonetheless, site instrumentation and analytical costs remain a significant disincentive to their implementation, despite recent advances in on-line technology. Indeed, in many cases the cost of piezometer installation is so prohibitive as to make the use of multilevel sampling infeasible. In such cases, the field hydrogeologist may need to consider employing wells with long-screened intervals, or open boreholes to monitor groundwater. However by following this path, it must be borne in mind that it will not be possible to determine the horizon supplying tracer to the well, should whole well monitoring methods be used. Multiple-depth sampling in an individual well can provide an alternative means of monitoring in such wells. However, as both Test 2 and Test 3 in this study have illustrated, an understanding of the dynamics of water flow in the well is essential prior to selecting monitoring points. Indeed, failure to consider this aspect may result in inappropriate sample depth selection, and unnecessary analyses of samples from multiple points may yield very similar tracer responses that are not reflective of horizons in contact with the well screen at the sampling point.

In a more general sense, the results of this study highlight the importance of preferential flow zones in controlling mass transport to water supply wells in highly heterogeneous porous systems. Moreover, bacteriophage breakthrough curves obtained during Test 2 indicate that although these zones have a strong attenuative capacity, they may also be the units that most easily facilitate the transport of reactive contaminants such as microorganisms. The attenuation of these contaminants may be due to kinetic processes where the degree of attenuation is dependant on the time the contaminant spends in the aquifer (R. Bales et al., 1991). Under such circumstances, grain size and attenuative capacity of the minerals contained in these beds can prove critical in determining the degree of attenuation of reactive contaminants. Consequently compositional and textural characterisation of these zones provides critically important information which may provide an insight into the vulnerability of a particular aquifer to groundwater contamination. Nonetheless, the inability to visually identify preferential flow zones from borehole cores partially reflects shortcomings in currently used site investigation techniques employed in sand and gravel aquifers. The anticipated application of recently developed geophysical and geological investigative techniques, such as rotasonic drilling, in the future is expected to improve this situation.

Summary

Groundwater pollution by microbiological contaminants is a widespread problem in many parts of the developing and the developed world. Field-based tracer testing provides an important means of further understanding an aquifers vulnerability to this type of contamination. However, financial constraints often limit the number of points monitored during a test, particularly when multilevel sampling systems are employed. Open boreholes/wells with long screens offer an alternative means of monitoring tracer concentrations but may suffer from the disadvantage of simultaneously sampling many different geological units. In order to test mass transport rates of conservative and microbiological contaminants in a gravel aquifer, a comparative tracer tests were carried out employing solute and bacteriophage tracers. Responses were monitored in an observation well containing a 3 m long screen located 20 m down gradient of an injection well. Granulometric analyses of aquifer samples collected over the depth interval corresponding to the well screen in the observation well indicated that hydraulic conductivities varied by up to two orders of magnitude. Nonetheless solute and bacteriophage breakthrough curves generated from samples collected at different depths in the well using a peristaltic pump indicated a uniform response at the levels investigated. Subsequent solute tracer testing carried out using a mobile downhole fluorometer coupled with results of heat pulse flow meter vertical flow measurements demonstrated that tracers entered the monitoring well from a preferential flow zone no thicker than 50 cm and subsequently flowed downward inside the well, before re-entering the aquifer at the base of the screened interval. The results of this study highlight the importance of preferential flow zones in influencing both solute and microbiological tracer responses in fluvioglacial gravels. Moreover, the distribution of tracer at the various depths monitored reflected the strong influence of the well water flow regime. Failure to visually identify the preferential zone in the borehole core illustrates some of the shortcomings of current site investigation techniques employed in sand and gravel deposits.

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Zusammenfassung

Grundwasserverschmutzung durch mikrobiologische Schadstoffe stellt ein in vielen Entwicklungs- und Industrieländern verbreitetes Problem dar. Markierungsversuche sind ein geeignetes Mittel, die Anfälligkeit eines Grundwasserleiters gegenüber diesem Schadstofftyp abzuschätzen. Jedoch ist aus finanziellen Gründen die Anzahl von Beobachtungspunkten meist deutlich begrenzt, besonders wenn tiefenspezifische Probenahmesysteme verwendet werden. Alternativ können Bohrungen bzw. durchge-

hend verfilterte Grundwassermessstellen eingesetzt werden, mit dem Nachteil, dass der Tracerdurchgang dann nur gleichzeitig über die gesamte Filterstrecke und eventuell über mehrere geologische Einheiten erfasst werden kann. Um den Transport von löslichen und mikrobiologischen Schadstoffen in einem Kiesgrundwasserleiter zu untersuchen, wurde ein vergleichender Markierungsversuch mit löslichen Tracern und Bakteriophagen durchgeführt. Die Probenahme erfolgte an einer auf 3 m durchgängig verfilterten Grundwassermessstelle 20 m unterstromig des Eingabebrunnens. Granulometrische Analysen des Bohrgutes zeigen an, dass die hydraulische Leitfähigkeit des Grundwasserleiters entlang der Filterstrecke um bis zu zwei Größenordnungen variiert. Dennoch wurden in den Proben, die mittels einer peristaltischen Pumpe in unterschiedlicher Tiefe entnommen wurden, sowohl für die löslichen Tracer als auch für die Bakteriophagen tiefenunabhängige, einheitliche Durchgangskurven registriert. Weitere Markierungsversuche erfolgten mit löslichen Stoffen, welche in-situ mittels eines mobilen Fluorimeters entlang der Filterstrecke nachgewiesen wurden. Diese Ergebnisse belegen, in Verbindung mit Messungen des vertikalen Wärmeflusses, dass die Tracer die Grundwassermessstelle nur an einem begrenzten Bereich bevorzugten Fließens von nur etwa 50 cm erreichen, um dann von dort innerhalb der Verrohrung nach unten abzusinken und am unteren Ende der Verfilterung wieder in den Aquifer auszutreten. Diese Untersuchungen veranschaulichen die Bedeutung bevorzugter Fließwege für den Transport von löslichen und mikrobiologischen Tracern in fluvioglazialen Kiesen. Zudem wird deutlich, dass die vertikale Verteilung eines Tracers in unterschiedlicher Tiefe der Beobachtungsmessstelle entscheidend vom Fließverhalten innerhalb der Verrohrung abhängt. Das Manko gängiger Untersuchungsmethoden zur geologischen Charakterisierung von Sand- und Kiesablagerungen ist allerdings, dass Zonen bevorzugten Fließens nicht visuell erkennbar sind.

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Schlüsselwörter: Messstelle, Verfilterung, Tracer, Fluorimeter, bevorzugtes Fließen, Kiesgrundwasserleiter