Tracers and Modelling in Hydrogeology (Proceedings of the TraM'2000 Conference held at Liège, Belgium, May 2000). IAHS Publ. no. 262, 2000.

Information gain using single tracers under steady state and transient flow conditions: the Gårdsjön G1 multiple tracer experiments

GUNNAR LISCHEID, HOLGER LANGE & MICHAEL HAUHS

BITÖK, University of Bayreuth, Dr Hans Frisch Str. 1–3, D-95440 Bayreuth, Germany

e-mail: gunnar.lischeid@bitoek.uni-bayreuth.de

Abstract Tracer experiments are a common method of obtaining spatially integrated information about aquifer properties. However, the uncertainty of unique experiments can rarely be assessed. The Gårdsjön G1 roofed catchment was used to perform a series of steady state experiments with almost identical boundary conditions. Br, Cl, and ^{2}H tracers were applied in parallel. Tracer breakthrough curves are modelled by a two-region convection-dispersion model. Parameter values determined by inverse modelling critically depend on the underlying assumptions, e.g. whether a tracer is conservative or not cannot be assessed from the model alone. Furthermore, in the case of the Br tracer our experiments exhibit a clear dependency on the temporal scale of the measurements. In spite of very similar boundary conditions, the shapes of breakthrough curves, and the corresponding model parameter values obtained in different experiments, differ considerably. In addition, the transit time probabilities for steady and transient flow conditions differ substantially.

INTRODUCTION

Parameter values determined by applying conservative tracers usually are assumed to represent time-invariant aquifer properties. Tracer experiments at the field scale are seldom performed with different conservative tracers and hardly ever checked for reproducibility in time. The Gårdsjön G1 roofed catchment provides the nearly unique opportunity to perform steady state tracer experiments at the field scale with replicates with nearly identical boundary conditions.

SITE DESCRIPTION AND EXPERIMENTAL SETUP

The G1 catchment is located 15 km from the west coast of Sweden and 45 km north of Göteborg. It has an area of 6300 m^2. The vegetation is dominated by 80 to 100 year old Norway spruce. The soils are podzolic with high porosity. Mean soil depth over the catchment is 43 cm, varying between 0 and 140 cm (Nyberg, 1995). The bedrock is a gneissic granodiorite. A long-term acidification recovery experiment at the site commenced in 1991. To achieve de-acidification, a transparent plastic roof has been built. Natural precipitation is substituted by "pre-industrial" clean rain applied by a sprinkler system. The water is taken from Lake Gårdsjön. It is de-ionized and sea salt is added to simulate natural sea spray input. The setup and first results are described in detail by Moldan *et al.* (1998). For the experiments reported here, a sub-area of

1000 m^2 adjacent to the water divide was irrigated. The area of the total flow region, including the area between the weir and the irrigated subregion is about 2000 m^2. The minimum distance between single sprinklers and the weir is about 25 m and the maximum distance is 70 m. Total water storage of this area is roughly 530 m^3 under storm flow conditions such as imposed during the experiments (Lange *et al.*, 1996). The tracers were applied during steady state conditions as a short rectangular pulse of 15 min (Br) or 24 min (^2H) length, respectively. Additional boundary conditions for the experiments are given in Table 1.

Table 1 Setup of the three experiments.

	1993	1995	1996
Performed in	November	July	June–July
Duration of steady state	72 h	84 h	99 h
Mean sprinkling rate	3.95 $m^3 h^{-1}$	3.24 $m^3 h^{-1}$	3.44 $m^3 h^{-1}$
Tracer concentration	Br: 45 mg l^{-1}	Br: 446 mg l^{-1}	Br: 424 mg l^{-1}, δ‰ ^2H: 42900

RESULTS

The first increase of tracer concentration at the catchment's outlet was observed about 4 h after tracer application. During the first 12 h, the ^2H and Br breakthrough curves do not differ significantly (Fig. 1). Thereafter, the ratio between the normalized Br and ^2H concentration decreases almost monotonically, until it reaches a value of 0.2 after the first 48 h, and remains constant thereafter. As a consequence, the Br concentration peak is observed about 15 h before the ^2H peak passes the catchment's outlet. Cl concentration in the catchment's runoff starts to decrease nearly simultaneously with the end of the sea salt addition, and continues to decrease until the end of the experiment (Fig. 1).

Recovery rates up until the end of the steady state period were 14–15% for Br in the 1993, 1995 and 1996 experiments, and 58% for ^2H in 1996. However, in spite of very similar boundary conditions, Br breakthrough curves differ considerably for the three experiments (Fig. 2). In 1995, normalized time until peak breakthrough is about half that of the 1996 experiment.

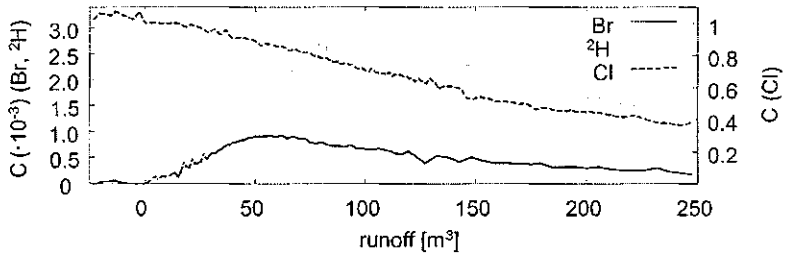

Fig. 1 Breakthrough curves for the 1996 experiment. Tracer concentration is normalized by subtracting the background concentration and dividing by the tracer input concentration (for Br and ^2H), or by dividing by the initial concentration (for Cl). Runoff is accumulated since the tracer application (for Br and ^2H), and since cessation of the sea salt addition (for Cl).

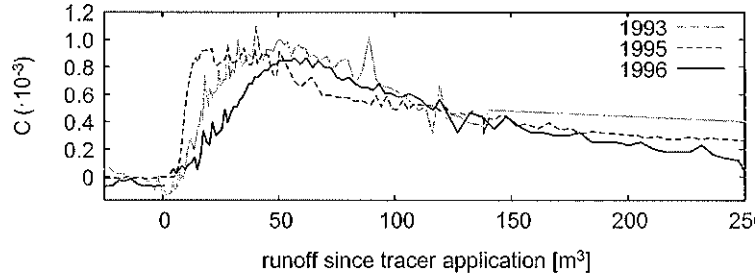

Fig. 2 Br breakthrough curves for the 1993, 1995 and 1996 experiments.

MODELLING

Fitting a convection dispersion model to observed breakthrough curves is a common way to determine tracer transport parameters. Here the well known CXTFIT 2.0 code (Toride *et al.*, 1995) is used. Taking into account physical non-equilibrium, dispersion, and sorption (for Br and Cl), parameter values for D (dispersion coefficient), β (fraction of the mobile water pool), ω (mass transfer coefficient between the mobile and immobile fraction) and μ (sorption coefficient) are determined by the model (see Toride *et al.*, 1995, and Lange *et al.*, 1996, for details). Mean pore water velocity υ can be assessed independently, based on the geometry of the flow region and mean pore volume (Nyberg, 1995). The one dimensional model was extended to two dimensions by assuming homogeneous parameters for the whole flow region, but different flow path lengths for single points.

In Table 2, model results are presented for the 1996 breakthrough curves. For Cl, two different parameter sets are presented. For the first, Cl is assumed to behave as a conservative tracer, yielding a substantially higher dispersion coefficient compared to that of the ^{2}H breakthrough. For the second, the sorption coefficient is allowed to differ from zero. As a consequence of the different shapes of the Br breakthrough curves parameter values determined by inverse modelling differ significantly (Table 2). It was not possible to map the 1995 Br breakthrough curves without re-adjusting the β and the ω values.

DISCUSSION

Different tracers

Being part of the water molecule, ^{2}H serves as a benchmark against which to judge the conservative behaviour of any tracer. Although often used as conservative tracers, Br

Table 2 Parameter values for different breakthrough curves. The 95% confidence interval is given for values determined by inverse modelling.

Tracer	v	D	β	ω	μ	r^2
^{2}H 1996	5.5	83.2 ± 1.8	0.42 ± 0.01	0.763 ± 0.03	0	0.984
Br 1996	5.5	103.3 ± 3.8	0.42	0.763	2.5 ± 0.2	0.959
Cl 1996	5.5	165.0 ± 4.3	0.42	0.08 ± 0.02	0	0.997
	5.5	83.0 ± 0.1	0.42	0.763	0.5 ± 0.1	0.997
Br 1995	4.9	148.0 ± 16.6	0.25 ± 0.02	8.2 ± 0.99	2.3 ± 0.2	0.963
Br 1993	6.6	155.3 ± 7.7	0.42	0.763	3.6 ± 0.2	0.914

and Cl clearly exhibit a different behaviour. It is remarkable that the modelling exercise cannot substitute the ^{2}H benchmark in the case of Cl dilution. On the other hand, there is a clear scale effect with respect to Br. This might reflect the transition from transport dominated by quickly draining pores to a transport regime dominated by smaller pores in the later phase of the experiment. The effect of the latter is rarely seen in soil column experiments.

Reproducibility of parameters

Our results reveal a marked inter-annual variability of the fitted parameter values that far exceeds the expected range. Although we were rather successful at getting the system into a hydrological steady state regardless of the preceding conditions, this was obviously not true of all the properties relevant for solute transport. The reason for this can only be speculated on so far. Nevertheless, this casts substantial doubt on the common interpretation of the parameters determined as representing time-invariant properties.

Steady state *vs* transient conditions

Replacing natural rain by de-ionized water from Lake Gårdsjön imposed a shift with respect to ^{18}O values that has been used for a tracer study under transient boundary conditions (Rodhe *et al.*, 1996). In this analysis, a flow-proportionally adjusted time scale ("flow time") is used:

$$t' = \int_{t_0}^{t} q(t)\,\mathrm{d}t / \overline{q}$$

where $\overline{q}$ denotes mean discharge depth (305 mm year^{-1}). The resulting transit time probability distribution for our 1996 ^{2}H data is compared to the ^{18}O data in Fig. 3. Using a generalized version of the transit time distribution function used in Rodhe *et al.* (1996), namely:

$$g(t) = a_3 \frac{a_1}{a_2} t^{a_1 - 1} \exp\left(-\frac{t^{a_1}}{a_2}\right)$$

where a_1, a_2 and a_3 are the parameters to be fitted ($a_3 = 1$ in the case of Rodhe *et al.*, 1996), we obtain the result shown in Fig. 3. The statistics of this fit are given in Table 3. It is obvious that the two distributions differ significantly.

Acknowledgements We highly appreciate the support of IVL in Göteburg, of the BITÖK central laboratory, and of numerous students who helped in performing the experiments. This work was funded by the German Federal Ministry for Education, Science, Research and Technology under grant nos 0339476 B and 0339476 C.

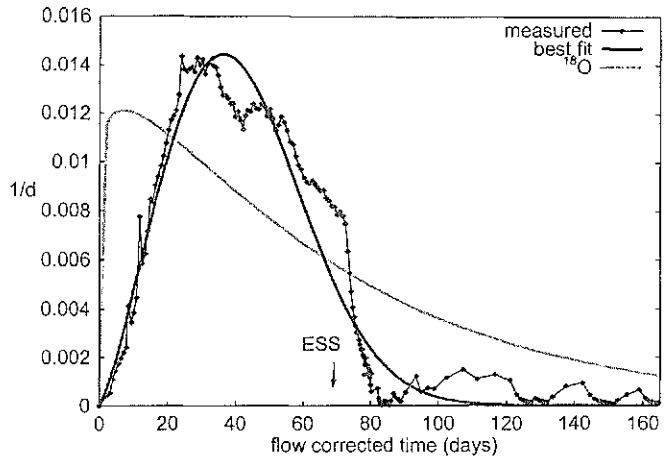

Fig. 3 Reconstruction of transit time probability against flow corrected time for the ^{2}H tracer 1996. For this experiment, the 165 days shown correspond to a runoff volume of 270 mm. The best fit for the ^{18}O tracer experiment under transient flow conditions (Rodhe *et al.*, 1996) is shown for comparison. ESS denotes End of Steady State for our experiment.

Table 3 Best fit parameters and estimation errors (1 σ) for the transit time distributions.

	a_1	a_2 (10^3 days)	a_3	r^2
This report	2.28 ± 0.04	6.33 ± 0.87	0.72 ± 0.01	0.94
Rodhe *et al.* (1996)	1.097	0.101	1 (not fitted)	

REFERENCES

Lange, H., Lischeid, G., Hoch, R. & Hauhs, M. (1996) Water flow paths and residence times in a small headwater catchment at Gårdsjön, Sweden, during steady state storm flow conditions. *Wat. Resour. Res.* **32**, 1689–1698.

Moldan, F., Andersson, I., Bishop, K. & Hultberg, H. (1998) Catchment scale acidification reversal experiment at Gårdsjön, south-west Sweden—assessment of the experimental design. In: *Experimental Reversal of Acid Rain Effects: the Gårdsjön Project* (ed. by H. Hultberg & R. A. Skeffington), 85 -108. John Wiley, New York, USA.

Nyberg, L. (1995) Water flow path interactions with soil hydraulic properties in till soil at Gårdsjön, Sweden. *J. Hydrol.* **170**, 255–275.

Rodhe, A., Nyberg, L. & Bishop, K. H. (1996) Transit times for water in a small till catchment from a step shift in the oxygen-18 content of the water input. *Wat. Resour. Res.* **32**, 3497–3511.

Toride, N., Leij, F. J. & van Genuchten, M. Th. (1995) The CXTFIT code for estimating transport parameters from laboratory or field tracer experiments – version 2.0. *Research Report no. 137, US Salinity Laboratory, Riverside, USA.*