Tracer Investigations at the Research Station "Wagna" (Leibnitzer Feld, Austria) to detect the Role of the Unsaturated Zone for Groundwater Protection

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ABSTRACT: Tracer investigation and numerical modelling of the movement of water and solids in the unsaturated and saturated zone of an aquifer enables to quantitatively predict the impact of different measures on to the whole system. However, setting up a model and determining model parameters still calls for substantial research efforts. The results of tracing experiments in the unsaturated zone of a quaternary gravel fill were used to prove the measuring and sampling devices on their ability to detect transient transport phenomena of water and solutes, to illustrate the differences between hydraulic reaction of water content on infiltration events and the velocity of solute movement in the unsaturated zone, to estimate hydraulic parameters of soil horizons as a basis for the calibration of solute transport models in the unsaturated zone, to quantify different flow components using advection-dispersion transport modelling and to correct measured flow data of field lysimeters.

1 PROBLEM DEFINITION AND CHARACTERISATION OF THE TEST SITE

The area of investigation, the so called Leibnitzer Feld is situated in the lower Mur valley, which is filled up with quaternary gravel and sand with relatively high permeability and a thickness of 10 to 15 m. It represents an important aquifer which is intensively used for common water supply of the region (Fank 1999, Fank & Harum 1994).

Based on the knowledge that key processes which contributed to the nitrate problem in the Leibnitzer Feld predominantly take place in the vadose zone in 1991 an experimental station was built which enables to monitor the movement of water and solids from the atmosphere through the soil (~100 cm) and unsaturated sand and gravel (~450 cm) into the saturated quaternary valley fill. The most important function of the station is it's ability to explore the movement of water and solids by means of hydrochemical and isotope-hydrological analyses based on natural land use practices (Fank 1999, Fank & Harum 1994).

2 TRACING EXPERIMENTS

In spring 1993 combined tracer experiments has been carried out (Fank & Harum 1994). The period before the tracer injection on April 14th, 1993 was characterised by a long dry weather period and a winter without snow cover. Nevertheless the saturation of the soil profile was near the field capacity. The soil temperatures in all depths indicated that the soils had not been frozen for some weeks.

The injection of the tracers was carried out in the evening of April 14th, 1993. 6 kg of sodium-bromide were dissolved and injected by sprinkler irrigation during 6 hours on both fields (area 10.5 * 9 m on each test site). The regularity of distribution of the artificial rainfall over the irrigated area was controlled by 10 precipitation gages. The amount of irrigated water (app. 30 - 40 mm) is corresponding to a normal summer thunderstorm event.

3 RESULTS

Figure 1 shows the bromide breakthrough curves in different depths The soil water samples from different sampling systems (Fank & Harum 1994) show well comparable concentrations of bromide, depending on the different residence time in depth.

The shape of the tracer breakthrough curves depend on the hydro-meteorological boundary conditions: infiltration causes tracer movement downward and results in concentration peaks. During stagnant periods the concentration of the tracer is nearly constant in time. The tracer breakthrough in the soil cover (root zone; 70 cm below surface) show effects of movement through macro-pores. The measurement equipment enables to detect transport processes in the unsaturated zone.

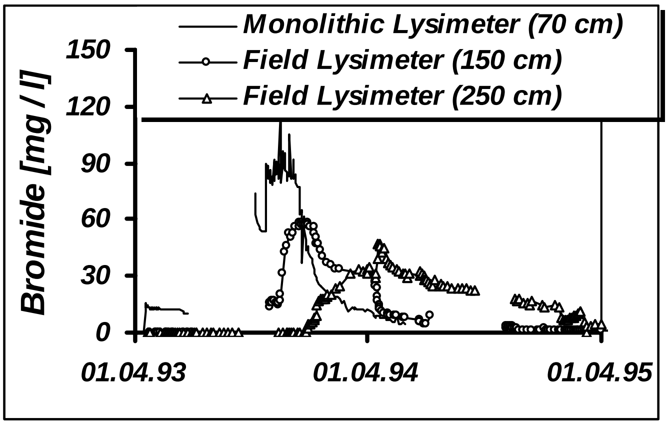

Figure 1. Comparison of bromide concentration breakthrough curves in different depths (70, 150 and 250 cm below surface).

3.1 *Hydraulic reaction and water movement*

Beside sampling and analysing soil water from different depths TDR-probes are installed in the soil profiles to detect the water content of the different horizons (Fank & Harum 1994). Figure 2 shows the alteration of water content in different depths as a significant reaction on the irrigation event at injection time of the tracing experiment.

Within a few days after irrigation an increase of the water content in all soil horizons of the profile is detected, the amount of the raise depending on the soil physical parameters (3 to 4 % in the soil cover, app. 1 % in the unsaturated gravel and sand).

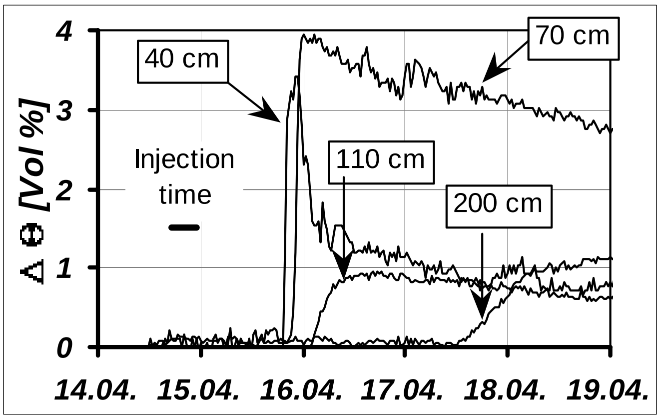

Figure 2. Changing of water content in different depth (40, 70, 110 and 200 cm below surface) as a hydraulic reaction on irrigation of 40 mm at injection time.

Comparing Figure 2 with Figure 1 a clear differentiation between the hydraulic reaction (piston flow effect) and water transport (visualised using bromide transport) must be done: 200 cm below surface the increasing of water content starts 3 d after irrigation, the first appearance of the tracer is detected app. 230 d after injection. As shown in Table 1 the dominant tracer velocity v_a (transport time of peak concentration) from the surface to 2 m depth is app. 2 m/y.

3.2 *Estimation of hydraulic parameters*

To describe the spreading of solutes from the flow paths in saturated groundwater flow the concept of dispersion is mostly used. To estimate the coefficient of dispersion from tracing experiments the calculation of "Peclet typecurves" may be used (Sauty 1977). For one-dimensional transport normalised time – concentration curves are calculated using Equation (1)

$$c_r = \frac{1}{\sqrt{t_r}} \cdot \exp\left[-\frac{Pe}{4 \cdot t_r} \cdot (1 - t_r)^2 \right] \quad (1)$$

where c_r = type curve concentration, t_r = type curve time and Pe = Peclet number.

Because flow in the unsaturated zone is a kind of one dimensional vertical transport this method was used evaluating the tracing experiment at research station Wagna. As shown in Figure 3 a Peclet typecurve was fitted to the measured and normalised tracer breakthrough curve varying the Peclet number.

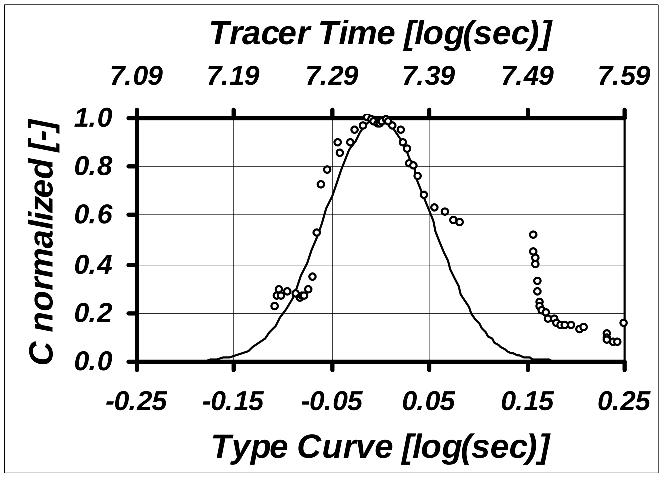

Figure 3. Fitting of Peclet Type Curve on the tracer breakthrough curve in 150 cm below surface.

Using the fitted Peclet number the longitudinal dispersion coefficient is calculated using Equation (2)

$$D_L = \frac{v_a \cdot x}{Pe} \quad (2)$$

where D_L = longitudinal dispersion coefficient, v_a = flow velocity, x = flow length and Pe = Peclet number.

Table 1 shows the flow velocity in the unsaturated zone and the calculated D_L for different measuring depths at two soil profiles at research station Wagna.

Table 1: Flow velocity (v_a) of the tracer depending on the length of the flow path (Depth) and evaluated longitudinal dispersion coefficient (D_L) in the unsaturated zone.

Depth [m]	v_a [cm/s]	D_L [cm²/s]
0.40	2.83E-06	1.13E-06
0.40	2.15E-06	8.61E-07
0.60	3.26E-06	1.96E-06

0.70	3.59E-06	1.80E-06
0.70	3.80E-06	2.96E-06
1.10	5.33E-06	4.88E-06
1.50	7.18E-06	1.08E-05
1.50	5.90E-06	8.04E-06
3.00	9.27E-06	3.48E-05

The dispersivity (D_L/v_a) in the soil cover is in a range of 0.4 to 0.8 cm, in the unsaturated gravel and sand the values are significantly higher (app. 1 to 3 cm).

As we know from earlier investigations (Klotz & Moser 1974) there is a strong dependency of the D_L from v_a in saturated groundwater flow. The same effect was detected in the unsaturated zone (Fank 1999).

Figure 3 shows the dependency between v_a and D_L in the unsaturated zone of the research station Wagna in comparison with modelling results in the saturated zone of comparable hydrogeological environments.

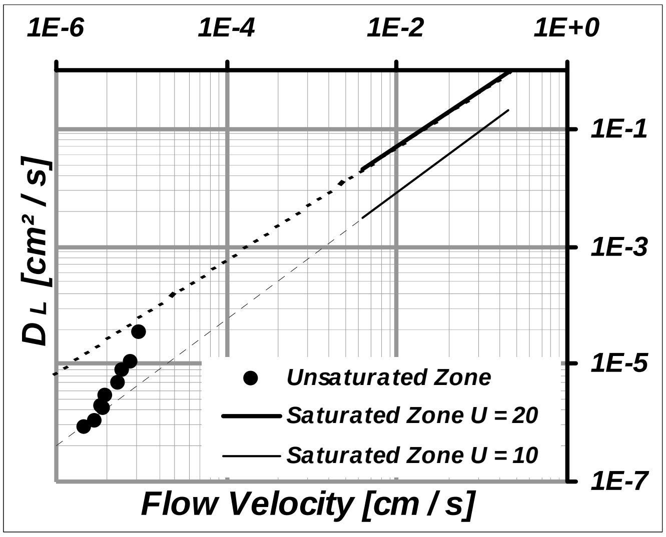

Figure 4. Dependency of the longitudinal dispersion coefficient (D_L) from flow velocity in the unsaturated zone in comparison to saturated sand (Klotz & Moser 1974).

Extrapolating the dependency in the saturated zone to the unsaturated zone taking into account the differences in v_a it is clearly visible, that the dispersivity is very well comparable. For the grain size unsimilarity d_{90}/d_{10} (U = 10) dispersivity ranges between 0.75 and 1 cm, for d_{80}/d_{20} (U = 20) the values are between 4.5 and 5 cm.

3.3 *Modeling of the tracer breakthrough curves*

Assuming the tracer application at research station Wagna as a momentum comparing the injection time to the tracer velocity in the unsaturated zone and assuming one dimensional flow in the unsaturated zone the partial differential advection-dispersion transport equation has an analytical solution.

Following Lenda & Zuber (1970) the solution of the one dimensional transport equation is shown in equation (4) using the initial and boundary conditions in (3).

$$C_{(x=0,t)} = \frac{m}{F \cdot n_e \cdot v_a}\delta(t); C_{(x>0,t)}; C_{(x\to\infty,t)} = 0; \quad \delta(t=0)=1; \delta(t \neq 0) = 0 \qquad (3)$$

$$C_{(x,t)} = \frac{m}{A \cdot n_e \cdot \sqrt{4\cdot\pi\cdot D_L \cdot t}} \cdot \exp\left[-\frac{(x - v_a \cdot t)^2}{4 \cdot t \cdot D_L}\right] \qquad (4)$$

where $C_{(x\ t)}$ = tracer concentration at distance x at time t, m = tracer mass, A = Area, n_e = effective porosity, D_L = longitudinal dispersion coefficient, v_a = flow velocity.

In humid climates – as in our investigation area – flow and transport of solutes through the unsaturated zone mainly depend on the hydro-climatic boundary conditions and the soil water deficit. Movement of tracers in time periods where the soil water content in the profile is near saturation mainly happen as a reaction on infiltration events. During summer months – where soil water deficit is high due to evapotranspiration losses – water and solutes in the unsaturated zone are more or less stagnant.

Therefore it seems to be possible to describe the movement of a solute – in our case of bromide as a tracer – as a series of advection-dispersion processes using the analytical solution in Equation (4). Figure 5 shows this attempt at a small field lysimeter in 150 cm below surface at research station Wagna.

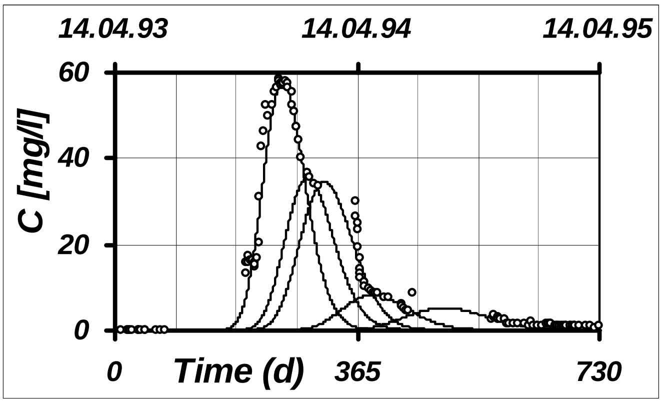

Figure 5. Numerical modelling of the tracer breakthrough curve (150 cm below surface) using the analytical solution of the transport equation.

The area A for calculation equals the surface of the lysimeter, x equals the distance from surface to the lysimeter surface (150 cm). The first flow component is calibrated using the results of evaluating the D_L. Further components are calibrated on the shape of the measured breakthrough curve in an iterative process varying v_a (D_L = dispersivity times v_a) and the tracer mass, where the sum of the tracer masses for the different components is controlled by the tracer output of the tracing experiment. The n_e is the main calibrated parameter – constant for all components and equals in this case 0.145 for best calibration quality.

At research station Wagna the characteristic curves of the different soil horizons are measured using tensiometers and TDR-probes (Fank 1999).

From evaluation of this data we know the effective porosity in any horizon of the unsaturated zone covering the lysimeter. From this date we estimate a mean n_e for the flow path from the surface to the lysimeter of 0.215, much higher then the result of calibration. On the other hand we know that this lysimeter gives to low values of groundwater recharge in comparison to some other lysimeters nearby due to construction problems at refilling the excavation.

Using the calibrated transport model we are able to calculate a correction factor for groundwater recharge data of the lysimeter (Equation 5):

$$C = \frac{n_{e(measured)}}{n_{e(modelled)}} \tag{5}$$

wher C = correction factor, $n_{e(measured)}$ = effective porosity from soil physics data and $n_{e(modelled)}$ = effective porosity from modelling results.

Figure 6 shows the cumulative sum curve of groundwater recharge from measured lysimeter data in comparison to groundwater recharge estimatetd from groundwater hydrograph. The method is presented in Fank (1999) and proofed on other lysimeter measurements and the results of numerical soil water modelling.

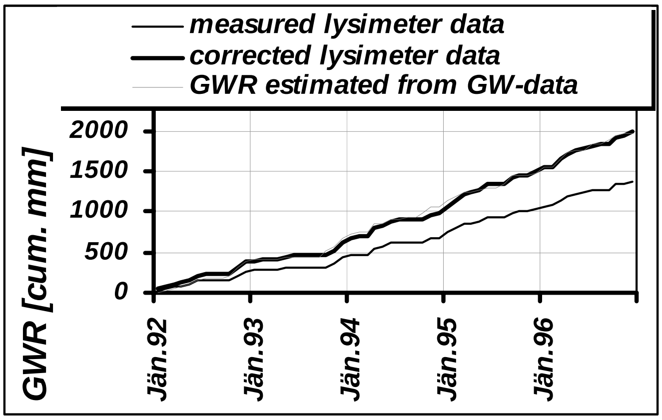

Figure 6. Comparison of cumulated sum of groundwater recharge (GWR [cum. mm]) between measured lysimeter data and corrected lysimeter data to ground water recharge estimated from ground water data (GW-data).

Multiplying the amount of groundwater recharge measured at the small field lysimeter at every time step with C and summing up over time the cumulative curve “corrected lysimeter data” shown in Figure 6 results. As visible there is practically no difference between the corrected data and the results of a very different method.

4 CONCLUSION

In spring 1993 combined tracer experiments have been carried out with the aim of comparison of solute transport and water movement and verification of the model concepts concerning solute transport in the unsaturated zone. The results of the tracing experiments were used

- To prove the measuring and sampling devices in the unsaturated zone on their ability to detect transient transport phenomena of water and solutes
- To illustrate the differences between hydraulic reaction of water content on infiltration events and the velocity of solute movement in the unsaturated zone
- To estimate hydraulic parameters of soil horizons as a basis for the calibration of solute transport models in the unsaturated zone
- To quantify different flow components using advection-dispersion transport modelling
- To correct measured flow data of field lysimeters

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