Tracer Experiments on Field Scale for Parameter Estimation to calibrate Numerical Transport Models

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Abstract

In September 2001 a tracing experiment has been worked out at the groundwater test field “Wagna” (400 * 300 m in the Mur valley aquifer system) using 75 kg of sodium bromide as tracer and injected during 20 minutes at the groundwater table (pulse injection). Due to the density of the solute the tracer has been distributed over the whole aquifer depth in a very short time.

For estimating the longitudinal dispersivity an analytical model for calibrating Peclet’ Typecurves on measured tracer breakthrough curves has been used. Transversal dispersivity was estimated using 2D-analytical model calibration. The results of parameter estimation on the field scale are compared to the results of a 2D-numerical bromide transport model for the test field based on a transient groundwater flow model.

Keywords

Tracing Experiment; Parameter Estimation; Modelling

Introduction

In 2001 at the research test field “Wagna” a new type of groundwater sampling site has been implemented for monitoring 3D ground water quality in shallow phreatic aquifers (Berg, 2003). The agricultural research area with a scale of 400 * 300 m is situated in the Murtal River Aquifer system in the southern part of Austria. In the saturated zone of the aquifer with a thickness ob about 3 m 36 sampling sites has been installed (Fig. 1), where samples can be taken in different depths and the hydraulic head was measured in short time intervals. From the cores of the bore holes the boundary between tertiary and quaternary sediments as aquiclude has been estimated. Groundwater recharge from infiltrating precipitation was measured at a lysimeter nearby.

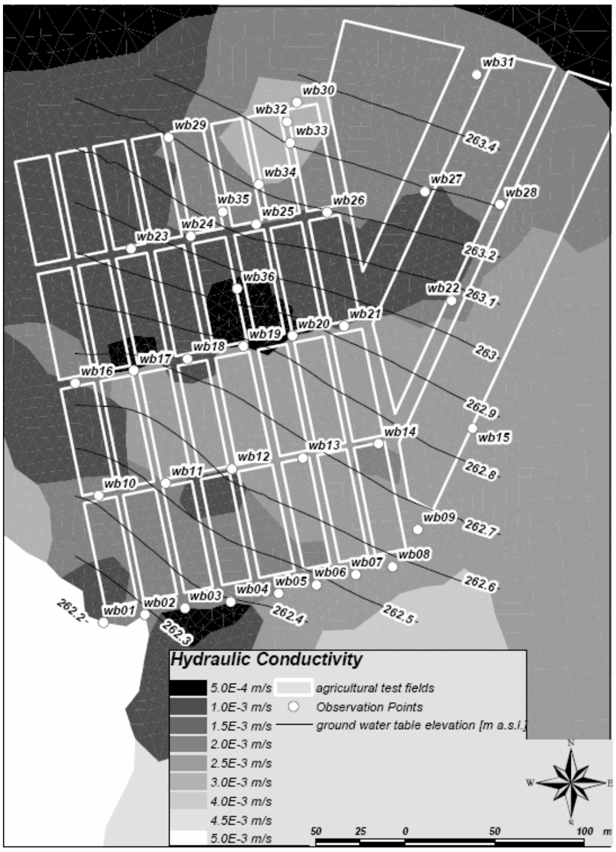

Fig. 1. Groundwater test field “Wagna”: distribution of hydraulic conductivity and observation wells for 3D groundwater quality monitoring.

Tracing experiment

In September 2001 a tracing experiment has been worked out using 75 kg of Sodium bromide as tracer diluted in 300 l of local groundwater and injected during 20 minutes at bore hole "wb30" (location see Fig. 1). The tracer solution has been injected at piezometer No. 3 10 cm below the actual groundwater table elevation (Fig. 2). The hydraulic reaction of the groundwater table on input has been observed at piezometer No. 4 and has been noted to be lower than 0.005 m. Due to the duration a pulse injection can be assumed. Vertical tracer distribution at injection place and tracer dilution was measured at piezometers No. 4 and No. 5. As visible in Fig. 2 the tracer concentration at injection point was lower than 1 ppm a week after injection.

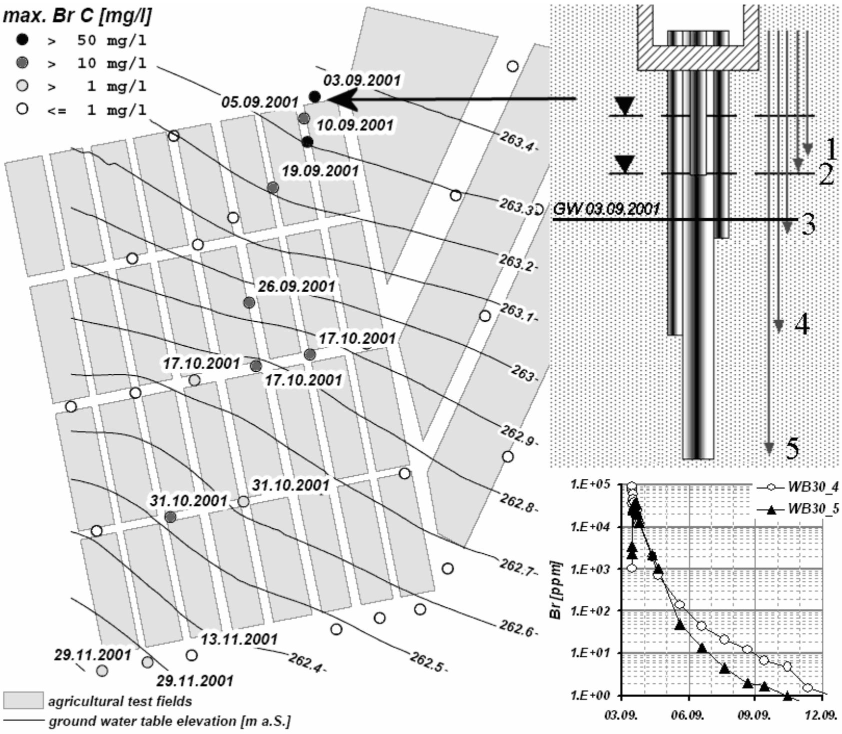

Fig. 2. Tracer (Br) injection at piezometer WB30_3 (September, 3rd 2001) 10 cm below ground water table. Control of tracer distribution with depth and dilution in piezometer WB30_4 and WB30_5 (concentration / time – diagram). Arrival time of tracer peak and peak concentration in the flow field downstream injection piezometer.

In Fig. 2 the distribution of the tracer cloud at the groundwater test field is shown as well, showing the arrival time of the tracer concentration peak and the measured peak concentration at the different observation wells. As expected the measured data indicate a movement of the tracer in ground water flow direction and a decrease of tracer concentration due to dilution and dispersion effects.

Due to aquifer geometry we assume 2D-groundwater flow and transport in horizontal direction. The homogeneity of vertical tracer distribution is visible in Fig. 3, where measured tracer concentration over time in different depths in the centre of the test field ("wb19", location see Fig. 1) are illustrated. In correlation to aquifer depth WB19_3 is situated close to the groundwater table, WB19_5 close to the aquiclude and WB19_4 in the middle between them in the center of the aquifer.

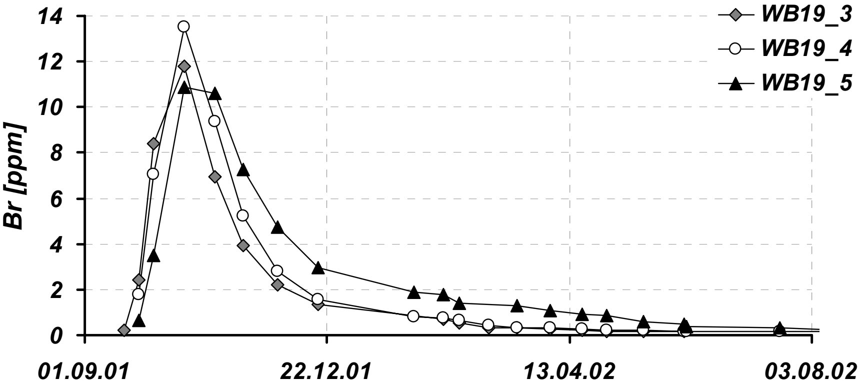

Fig. 3. Tracer (Br) distribution with depth in piezometers WB19_3, WB19_4 and WB19_5 in the center of the flow field (location see Fig. 1)

Parameter Estimation

The tracer breakthrough at the different measuring points has been used to estimate mean groundwater flow velocity (v_a) from the center of gravity of tracer concentration over time. The local hydraulic gradient (I) was estimated from hydraulic head measurement and interpolated contour lines of groundwater table elevation. From lysimeter investigations at the test field and evaluating groundwater table fluctuation (Fank, 1999) we assume a drain- and fillable pore volume (n_e) of about 0.15. Darcy's law led us to the estimation of hydraulic conductivity: $k_f = (v_a * n_e) / I$. The resulting set of hydraulic parameters for the different observation wells is shown in Table 1.

Table 1. Estimation of hydraulic and tracer transport parameters resulting from tracer test evaluation with: D = Distance between injection point and observation point, v_a = groundwater flow velocity, I = local hydraulic gradient, α_L = longitudinal dispersivity, α_T = transversal dispersivity, k_f = hydraulic conductivity (location of observation points see Fig. 1)

observation point	D [m]	v_a [m/d]	I [ ]	α_L [m]	α_T [m]	α_L/α_T	k_f [m/s]	α_L/D [ ]	α_T/D [ ]
WB01	312	3.00	0.004	18.35	1.08	17.00	0.002	0.059	0.003
WB03	275	4.52	0.003	19.64	1.03	19.00	0.003	0.071	0.004
WB11	227	3.23	0.003	12.61	0.63	20.00	0.002	0.056	0.003
WB12	220	3.69	0.003	14.67	0.73	20.00	0.002	0.067	0.003
WB18	155	4.44	0.004	10.33	0.34	30.00	0.002	0.067	0.002
WB19	146	2.92	0.004	9.13	0.37	25.00	0.001	0.063	0.003
WB20	135	3.55	0.004	9.00	0.36	25.00	0.002	0.067	0.003
WB36	110	4.02	0.003	8.46	0.42	20.00	0.002	0.077	0.004
WB33	23	2.76	0.001	4.66	0.17	28.00	0.006	0.200	0.007
WB34	51	4.70	0.003	5.67	0.27	21.00	0.004	0.111	0.005

The estimated spatially distributed hydraulic conductivity was used as initial value for the calibration of a transient groundwater flow model for the test field. The boundary conditions have been taken as time series of potential head from a regional groundwater flow model. The calibrated distribution of hydraulic conductivity is shown in Fig. 1. Fig. 4 demonstrates the quality of calibration comparing measured and calculated hydraulic head at different observation points (location see Fig. 1).

The horizontal black line in Fig. 4 indicates the duration of tracing experiment at the test field. We assume the groundwater flow direction and velocity as well described by the groundwater flow model for the whole time scale of the tracing experiment.

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 tracer transport from injection point (wb30 in Fig. 1) in groundwater flow direction normalized time – concentration curves were calculated and fitted to measured tracer breakthrough curves varying the Peclet number (Fig. 5). Using the fitted Peclet number longitudinal dispersion coefficient is calculated using the equation: $D_L = (v_a * D) / Pe$, where D_L = longitudinal dispersion coefficient, v_a = flow velocity, D = flow Distance (Table 1) and Pe = Peclet number. Longitudinal dispersivity (α_L) is estimated from (D_L/v_a).

Assuming the tracer application at wb30 a pulse injection comparing the injection time to the tracer velocity and assuming 2D parallel groundwater flow in an homogeneous and isotropic porous medium the partial differential advection-dispersion transport equation has an analytical solution. Using the analytical model of Schulz (1992) transversal dispersivity (α_T) may be calibrated on measured tracer distribution over time (Fig. 6 shows calibration quality on WB19_4 and resulting α_T for example). Calibrated values for α_T on all observation points which are tangent to the tracer cloud are shown in Table 1.

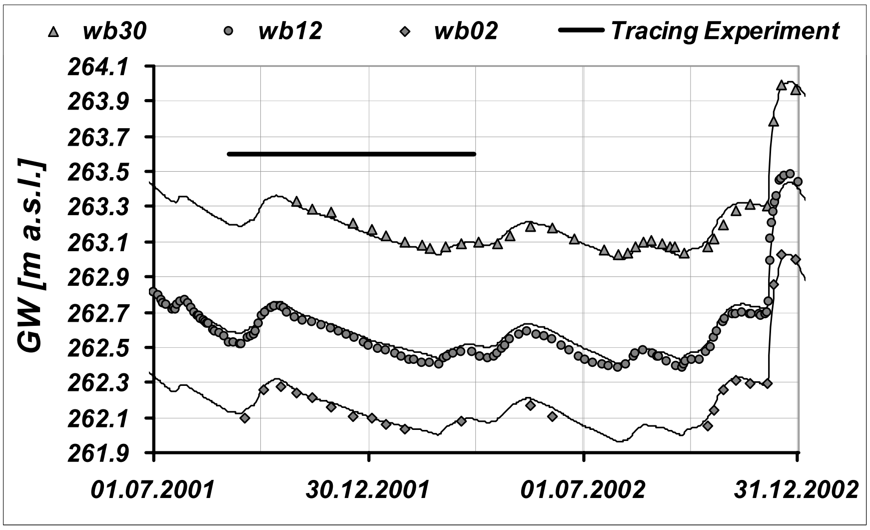

Fig. 4. Calibration of groundwater flow model – comparison of measured (points) and calculated (line) hydraulic head at different observation points (location see Fig. 1) and duration of tracing experiment (indicated with the horizontal black line).

PECLET-Number	***Pe***		**15**
Distance Injection Point - Observation Point [m]	***x***		**146**
mean groundwater velocity (tracing experiment) [m/s]	**v_a**	**C - center of gravity**	**3.0826E-05**
longitudinal dispersion coeffizient [m²/s]	**D_l**	**$(v_a * x) / Pe$**	**0.00030004**
longitudinal dispersivity [m]	α	**(D_l / v_a)**	**9.73**

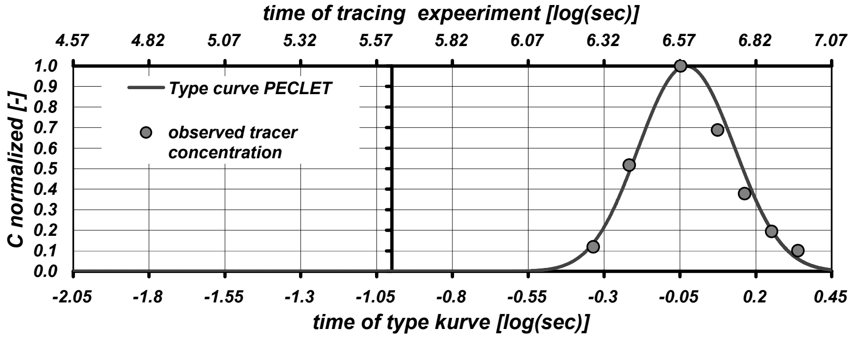

Fig. 5. Calibration of the Peclet's type curve evaluation (Sauty, 1977) at observation point WB19_4 (location see Fig. 1) and calculated transport parameters in groundwater flow direction using the analytical model.

tracer mass [kg]	**ΔM**	Br	58.243
aquifer thickness [m]	**m**	borehole logging	3
effective porosity [-]	**n_f**	evaluation of groundwater hydrograph	0.17
longitudinal dispersivity [m]	α_L	PECLET - evaluation	9.73
transversal dispersivity [m]	α_T	Kalibration	0.61
flow distance x - direction [m]	**x**	flow net	146.00
flow distance y - direction [m]	**y**	flow net	15.00
mean groundwater flow velocity [m/d]	**v_a**	Tracer breakthrough - center of gravity	3.25

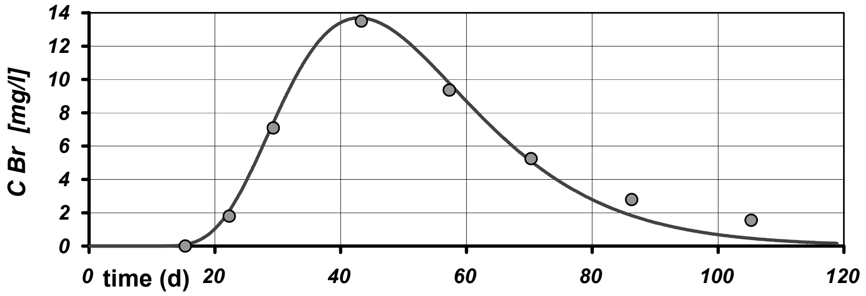

Fig. 6. Calibration of a 2D groundwater transport model (Schulz 1992) at observation point WB19_4 (location of "wb19" see Fig. 1) and calculated groundwater transport (dispersivity) parameter perpendicular to flow direction using the analytical model.

Schulz (1992) remarks a wide variety for longitudinal dispersivity in sandy and gravely porous aquifer systems. In field experiments values between 0.1 and 100 m for α_L have been investigated. Transversal dispersivity in most cases is much lower than α_L. A very wide variety of the relation α_L:α_T between 2:1 and 400:1 is given. For most cases a relation of 5:1 to 10:1 is assumed. In our experiment values of α_L in the range between 5 to 20 m were calculated with a relation of α_L:α_T from 17:1 to 30:1. The values shown in Table 1 agree very well with literature data.

A dependency of α_L on flow length is stated as well (Schulz, 1992). The same effect has been observed at the tracing experiment in Wagna. The dependency of α_L on the distance of the observation point from the injection point is shown in Fig. 7. At the observed distances between 25 and 300 m a linear correlation with high significance was found for α_L. A similar correlation has been investigated for α_T (Fig. 7). The concept of dispersivity assumes α to describe the in-homogeneity of the aquifer and be sediment constant. In most numerical models dispersivity is implemented as a material constant. Looking on literature data (Schulz, 1992) and on the results of the presented experiment a parameter like α/D (Table 1) describing solute distribution as a material parameter will give better information for the interpretation of tracer distribution from point source at field scale.

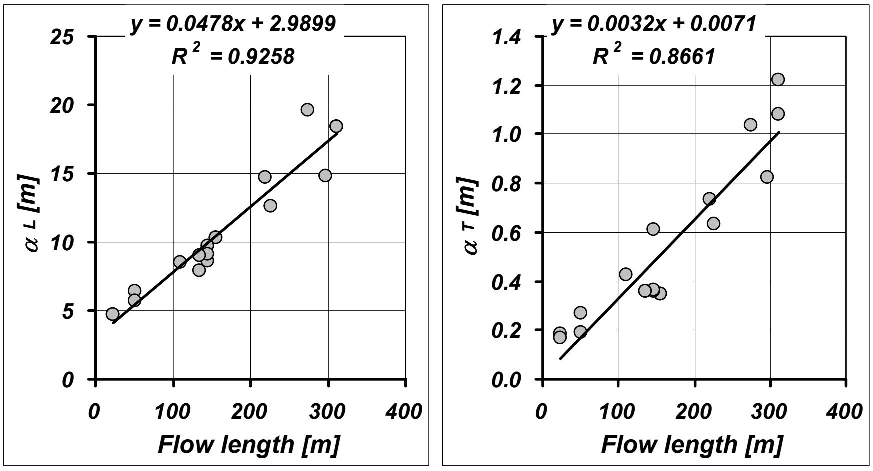

Fig. 7. Estimation of longitudinal and transversal dispersivity from tracing experiment using analytical modeling.

Calibration of a numerical tracer transport model

The results of analytical modelling to determine α_L and α_T were used as initial conditions for the calibration of a 2D horizontal numerical tracer transport model. Measured tracer breakthrough was used for calibration of the model. As shown in Fig. 8 the calibration of the model is well done on the central flow line of tracer transport with only few modification of longitudinal dispersivity: the spatial distribution of α_L show values between 2 m near injection point and 20 m at the end of the test field in a flow distance of about 300 m downstream “wb30”.

Problems arise in calibrating the transport model on observation points beside the central flow line as shown in Fig. 9: Although the results of analytical modeling α_T have been modified in some regions to values higher than 3 m it was not possible to fit measured tracer breakthrough and numerical modeling results at observation points “wb02” and “wb03”. Calculated tracer concentration values are much higher than the measured ones.

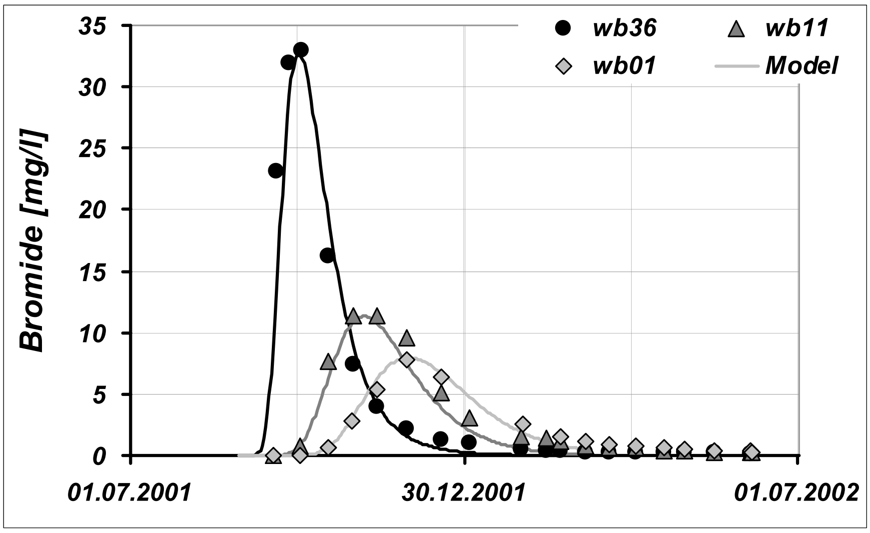

Fig. 8. Measured Bromide concentration breakthrough curves compared to the results of numerical modeling at observation points in central flow direction (location of observation points see Fig. 1)

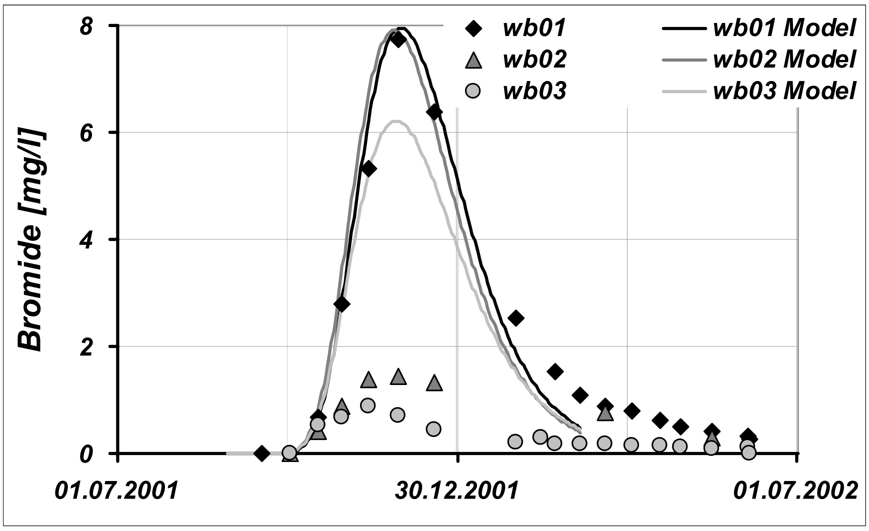

Fig. 9. Measured Bromide concentration breakthrough curves compared to the results of numerical modeling at observation points perpendicular to flow direction (location of observation points see Fig. 1)

Conclusion

The evaluation of a tracing experiment and the attempts to calculate tracer breakthrough using a 2D horizontal Finite Element transport model at different observation points in an intensively monitored groundwater test field in a shallow phreatic aquifer system led us to some conclusions:

- Monitoring tracer concentration data gives the possibility to visualize transport processes in groundwater
- The results of analytical modeling to estimate longitudinal dispersivity are well comparable to calibrated values used in a 2D horizontal Finite Element transport model
- Using the values of transversal dispersivity gathered from analytical modeling for calibrating a numerical transport model gives an overestimation of tracer concentration at observation points beside the central groundwater flow line in the test field
- The transversal dispersivity parameter in numerical modeling is extremely sensitive to unobserved transient groundwater flow processes.

References

Berg W (2003) Monitoring, Analysis and Interpretation of Nitrogenous components and their layered transport into the groundwater of a shallow quarternary aquifer (Leibnitzer Feld, WAGNA). PHD-Thesis, Inst f Geographie und Raumforschung, Karl Franzens Universität Graz, p 157

Fank J (1999) Die Bedeutung der ungesättigten Zone für Grundwasserneubildung und Nitratbefrachtung des Grundwassers in quartären Lockersediment-Aquiferen am Beispiel des Leibnitzer Feldes (Steiermark, Österreich). Beiträge zur Hydrogeologie, 49/50, pp. 101-388

Schulz HD (1992) Physikalische Grundlagen des Stofftransports im Untergrund. Geohydrologische Markierungstechnik, Lehrbuch der Hydrogeologie, 9, pp. 325-362,(Borntraeger) Stuttgart

Sauty JP (1977) Contribution à l'identification des paramètres de dispersion dans les aquifères par interprétation des expériences de tracage. – Bur. de Recherches Géol. et Minières; Dépt Hydrogéol 77SGN515HYD, p 157 , Orléans