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Reply to the comment of Marti Bayer-Raich, Jerker Jarsjö and Georg Teutsch on "Analysis of groundwater contamination using concentration-time series recorded during an integral pumping test: Bias introduced by strong concentration gradients within the plume (Zeru and Schäfer, 2005)"

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1. Overview

We thank Bayer-Raich et al. (2007-this issue) for taking an interest in our work. The research described by Zeru and Schäfer (2005) was conducted within the European project INCORE (Contract EVK1-CT-1999-00017) where the authors of the comment have been involved as participants. From our side, they have regularly been informed about the progress of our research (e.g. Zeru and Schäfer, 2003a,b). But unfortunately, and we do regret for the human difficulties encountered, which forced us now to state that this written comment of Bayer-Raich et al. is the first scientific feedback from them, keeping in mind that they were a part of the origin of the scientific and technical concept of the integral pumping test (IPT).

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Their comments are focussing principally on the fact that the bias introduced in the evaluation of an IPT, as discussed in Zeru and Schäfer (2005), is mainly due to a non constant longitudinal concentration gradient within the plume.

We entirely agree that in a hypothetical case of a plume, where a constant longitudinal concentration gradient is supposed to exist in each streamtube of the uniform flow field, the analytical solution as developed by Schwarz (2001) will give a correct concentration distribution in the control plane without any bias. To come to this conclusion, no extended mathematical developments are needed. The mass balance approach developed by Zeru (2004) for numerical inversion of concentration-time series recorded during an integral pumping test gives the same conclusion but in a more physical based way. For a given pumping time, the mass recovered in the well is assumed to be equal to the mass of dissolved contaminant comprised in the defined capture zone. In the case of an axisymmetrical distribution of the isochrones, the mass originating from each individual streamtube can be quantified by multiplying the given area (that is common to both the capture zone and the corresponding streamtube) by the aquifer thickness, the porosity and the mean concentration in the considered streamtube (Zeru, 2004). As long as the concentration distribution within each streamtube is symmetrical to the imaginary control plane (ICP), the mean concentrations will thus correspond to the unknown concentrations along the y-axis.

However, a constant longitudinal concentration gradient is not a very realistic assumption under field situation. We will show in Section 2 that even in the Borden field case which is known to be a relatively homogeneous aquifer with quite low dispersivities, concentration variation in flow direction due to dispersion processes is characterized by a non constant slope of concentration distribution. Coming up with this conclusion, the remarks of Bayer-Raich et al. (2007-this issue) (see Eq. (9) in their comment) on the validity of a concentration gradient ratio $\gamma(x,y)$ in the plume as defined by Zeru and Schäfer (2005) are not really pertinent. We cannot see any ambiguity of its use for error analysis during IPT-evaluation. As demonstrated in our research paper, γ can undergo strong variations within the plume, especially in a given ICP position. Hence, in order to characterize the plume over a defined capture zone around the IPT-well, one has to introduce a spatially averaged value of γ. Therefore, we used the so-called directional averaged gradient ratio for quantification of the bias introduced by strong concentration gradients in the plume, which are generally not constant over the capture zone.

Another key statement of Bayer-Raich et al. (2007-this issue) criticizes the dispersivity values chosen in our numerical model setup. In our opinion, the chosen longitudinal and transverse dispersivities are not unrealistically high. High dispersivities observed in field applications are mostly due to heterogeneities of the aquifer structure. Furthermore, in depth-averaged transport models, the disregarded vertical velocity variation results in an increase of dispersion coefficients with transport scale (e.g. Matheron and de Marsily, 1980; Gelhar and Axness, 1983; Schäfer and Kobus, 1989). In addition, in field studies it is most likely that the plume will encounter large-scale heterogeneities that influence plume evolution beyond that observed in a statistically homogeneous aquifer. The problem of dispersion in natural media is quite complex. More recently, a large number of publications are discussing these scale effects and the influence of nonequilibrium conditions on the dispersion tensor (e.g. Quintard and Whitaker, 1994; Berkowitz and Scher, 1995; Zhang and Neuman, 1996; Cushman and Moroni, 2001).

Referring to dispersivities observed in real heterogeneous aquifers, the Rhine valley is quite a good example. It contains an important quaternary sandy-gravel aquifer, which is known for its high permeable heterogeneous structure. A large number of numerical studies using two-dimensional transport models have been conducted in the last two decades in order to characterize observed chlorinated solvent plumes at different field sites. For instance, in the case studies