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Hydrology and Earth System Sciences Discussions

Interactive comment on "Detection of contaminant plumes released from landfills" *by* N. B. Yenigül et al.

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1 General Remarks

The paper presents results of two-dimensional numerical and analytical studies on the detection of a conservative compound, introduced by a point source, by groundwater sampling in observation wells. In principle, the question posed by the authors is of large practical relevance. Designing monitoring-well systems in heterogeneous aquifers is challenging also from a scientific standpoint of view. Unfortunately, the contribution of the authors is not up to date regarding dispersion theory in heterogeneous formations. There is a severe mismatch of concepts (see below). The techniques used by the authors are well established, and I don't see the innovation in the work.

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Interactive Discussion

Discussion Paper

For the analysis of homogeneous aquifers, the authors use well established analytical expressions of conservative solute transport. Within this framework, computing the width of a required normalized concentration is straightforward. From a practical standpoint, however, this result is irrelevant because homogeneous aquifers don't exist.

The true challenge lies in spatial variability, leading to plume meandering and (in the given context more importantly) lateral squeezing and stretching of the plume (Rahman et al., 2005). As has been discussed by various authors, linear stochastic theory predicts minimal enhancement of lateral mixing by heterogeneity (Gelhar and Axness, 1983; Dentz et al., 2000; Fiori and Dagan, 2000), particularly in 2-D, where twisting of streamlines is impossible. In the framework of the study, longitudinal macrodispersion is of minor importance.

Obviously, the authors are not aware of the differences between absolute and relative dispersion (e.g. Andricevic and Cvetkovic, 1998), also denoted ensemble and effective dispersion (e.g. Dentz et al., 2000):

- Absolute (or ensemble) dispersion describes how the second central moments of the ensemble-averaged concentration change with time. For a point-like injection, these moments quantify to the largest extent the uncertainty of tagging the plume's center of mass. That is, the spreading computed by absolute dispersion coefficients is not observable in a single realization, such as the true one.

- Relative (or effective) dispersion describes the expected rate of change of spatial moments in single realizations. This is for the given study the relevant quantity.

Since the authors use a particle method in their numerical simulations, the Lagrangian framework of stochastic subsurface hydrology would be relevant. In this framework, the main quantity of interest is the two-particle semi-variogram of lateral displacement for zero initial separation, which is identical to the difference between the one-particle

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variance and the two-particle covariance of lateral displacement for zero initial separation. Rigorous first-order solutions exist in the spectral domain (Fiori and Dagan, 2000). Identical expressions were derived by Dentz et al. (2000) using an Eulerian approach. Extensions to transient flow have been presented by Cirpka and Attinger (2003) and Dentz and Carrera (2003, 2005). Eq. (48) of Cirpka and Attinger (2003) gives an approximate solution in the spatial domain. More elaborate approximate expressions are given by Dentz and Carrera (2003, 2005). Matlab codes for numerical evaluation of the spectral equations can be downloaded from free web sites.

The authors do not make a distinction between absolute and relative dispersion whatsoever. Instead, they use the asymptotic macrodispersion coefficients of Gelhar and Axness (1983) (which are ensemble dispersion coefficients) as if they were material properties of the formation. While they write about ”effective (macro) dispersivities” they mean ensemble dispersivities as stated above. They also neglect the fact that macroscopic dispersion coefficients depend on travel time (e.g. Dagan, 1988).

Rather than describing the particle-tracking/random-walk method (which has been introduced into groundwater hydrology more than 20 years ago), the authors should address the real scientific questions, namely:

- Are the first-order expressions for relative (or effective) dispersion in heterogeneous media accurate enough to be used for the design monitoring networks?
- These analytical expressions are by themselves ensemble averages. Therefore, how important is the (analytically not quantified) uncertainty of relative dispersion coefficients?
- Since the width of a plume in a heterogeneous formation varies due to velocity fluctuations, it may be worth analyzing whether the probabilistic distribution of the width can be estimated from known expressions of uncertainty (e.g. the variance of velocity). This could be mapped to a more reliable probability of detecting the

plume.

Obviously, these questions have not even been posed by the authors. Therefore, I recommend more than major revisions of the manuscript before acceptance.

2 Specific Comments

1. Title

   The title is misleading. The reader gets the wrong impression that the authors study real landfill plumes, while in reality they only perform numerical simulations in virtual aquifers.

2. Page 820, Line 4

   ”In this study, we analyze hypothetical test cases to quantify the detection probability...”

3. Page 820, Lines 9-10 and many times thereafter

   The authors do not explain what they mean by ”effective (macro) dispersivities”. As discussed above, their macrodispersivities are ensemble dispersivities and not effective dispersivities.

4. Page 820, Line 21

   ”introduced into the groundwater” rather than ”in”

5. Page 822, Line 20

   ”of a particular analytical model under heterogeneous aquifer condition” (eliminate spurious ”n” and change preposition)

6. Page 822, Lines 21-28

   In the given context, replacing the heterogeneous aquifer by a uniform aquifer with high conductivity is not the worst case. The plume does not get larger with larger velocity (which would be even good for the purpose of plume detection). Increasing the velocities leads to identical plumes, but at earlier times. In the framework of the study, the problem of heterogeneity is that the plume meanders and changes its width according to the velocity fluctuations. That is, the worst case would be a narrow, elongated gravel bar in the middle of two observation wells.

7. Page 823

   As stated above, the analytical expressions of Gelhar and Axness (1983) are for asymptotical ensemble dispersion. These expressions do neither hold at early times nor can they be used to estimate the width of a single plume in a single realization.

8. Page 824, Line 9

   ”conjugate gradient method” rather than ”conjugate method”

9. Page 824, Line 11

   Eliminate ”as a function of and”

10. Section 2.2

    The particle-tracking/random-walk method is well described in the literature. This section can be eliminated almost entirely. The only point needing description is the way how the detection was simulated.

11. Equation 9

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Obviously, the detection probability depends on the size of the grid cell $\Delta x \Delta y$, which is not given by the authors. The spacing should be representative for a typical observation well (diameter smaller 0.1m). Accounting for the flow focusing effect of the well, a size of 0.2m may be acceptable. Any value larger than that will lead to biased results.

12. Page 828, Line 3

    ”... particles released at time t_1 will follow the same paths as particles released at t_2.”

13. Page 829, Paragraph following Eq. (11)

    The authors got the arguments upside down: The grid spacing must be small enough to resolve the concentration field. If Δx is larger than σ, averaging over a cell leads to considerable artificial dispersion. Rather than smearing the analytical distribution, the authors should use a numerical solution that is acceptable. Otherwise the concentrations are biased.

14. Page 829, last paragraph

    It is easy to show that in the steady state longitudinal dispersion becomes negligible for the concentration distribution. In this case, one can use the simplified analytical expression of Domenico and Palciauskas (1982).

15. Section 3.2

    As mentioned above, there is a severe conceptual mismatch in the way how the authors consider dispersion in heterogeneous media. Even the expressions for ensemble dispersion are not correct: ıtemize

16. The macrodispersivities increase with time until the asymptotic value is reached. As a consequence, the variances of the spatial distributions are NOT tA_L^∞ and tA_T^∞, but $\int_0^t \tau A_L(\tau) d\tau$ and $\int_0^t \tau A_T(\tau) d\tau$, respectively. Also, it is known that the

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ensemble concentration does not follow exactly a Gaussian distribution (Dagan Neuman, 1991).

17. In 2-D, the effective conductivity of an isotropic formation is indeed the geometric mean of the conductivity distribution, so that γ equals one.

18. Notation in Section 3.3

    The variable "l" is difficult to distinguish from the number "1", at least with the fonts used by HESS. Please use a different notation (maybe "λ").

19. Page 833, Line 8

    Please use m/s as units for conductivity rather than m/d.

20. Page 834

    The study on the number of particles released in particle-tracking is not particularly exciting. If using 8000 particles is considered to be computationally demanding, the code cannot be efficient.

21. Results in general

    As stated above, I totally miss a comparison to what would be expected by modern stochastic theory. This lack is not compensated by presenting various plots.

22. Page 842, final paragraph of manuscript

    The authors' findings about the applicability of ensemble dispersion coefficients contain no new information. The entire discussion on effective dispersion, started 1988 by Kitanidis, relates exactly to the point that real plumes spread much less than the ensemble concentration. Since stochastic theory has reached the point to predict this difference, the authors could compare their results to the advanced theory. Without such a comparison, the study is useless.

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