Interactive comment on “On the Conceptual Complexity of Non-Point Source Management: Impact of Spatial Variability” by

Christopher V. Henri et al.

Referee #1 Evaluations

Overview

This is an interesting work that brings together many contributions in the field of probabilistic risk assessment (PRA) in aquifers to investigate transport of non-point sources (NPS). The authors explore parameters such as recharge rates and contaminant loadings in the final model output. Furthermore, the authors attempt to reduce the complexity of the model by upscaling a set of spatially/temporally variable quantities, such as the hydraulic conductivity, on the management of NPS. Through the use of numerical simulations, the authors provide an analysis that couples vadose zone, aquifers and land use in a single framework.

I enjoyed reading this paper given that it aims in bringing in elements of stochastic hydrogeology into decision making. The material is well written and organized. The illustrations are clear and well depicted. The referencing is also appropriate although some contributions in the PRA of contaminated aquifers are missing. This is not a big issue. Through the use of scaling arguments (i.e. compliance planes, source sizes etc) the authors make a compelling argument to evoke upscaling for the problem at hand. They claim that due to significant mixing in the compliance plane and the lack of significant variability in NPS solutes, the uncertainty in predictions are reduced thus leading more simplified approaches for modeling such complex systems. Results indicate that the mass arrival time distributions are not that sensitive to the spatial variability of recharge and solute loading whereas some sensitivity is observed for the concentration signal and capture zone estimation. The authors also show that homogenization of the conductivity affects the uncertainty of arrival times.

> Thank you for your overall positive evaluation of the manuscript and for your interest. We hope that our answers to your specific comments will clarify your concerns.

Specific comments

- The authors refer to the word ergodicity multiple times. Ergodicity in what? I think they are referring to ergodicity in the transport behavior. If so, provide a quantitative measure of what ergodicity is. For example, the ratio between the source zone dimension and correlation scale needs to be large. If this is the case, then why one would need to quantify uncertainty due to the conductivity field? The spatial statistics is representative of the ensemble statistics. This needs to be better discussed.

  > See response after the next bullet.

- I am not sure if I missed this in the text but it would be interesting to see if the upscaled dispersion reaches its Fickian limit. Looking at figure SM6, it seems that this is not the case and therefore, transport is still subject to uncertainty. To my understanding, based on the histograms, these upscaled dispersion coefficients reported in figure SM6 are not the ones in the Fickian limit and therefore ergodicity is not attained. So how is it that the authors claim “ergodicity” in this paper?

Thank you for raising your concern about ergodicity in these two comments. The context in which the term was used in the manuscript was, indeed, unclear.

The assumption of ergodicity is here employed NOT in the sense that we assume the NPS plume to be so large that there is no variability in plume moments between realizations. Instead, we here employ the ergodicity hypothesis in the same way as described, e.g., by Rajaram (2002) or Gelhar (1993). There, a single large realization (spatially extending over many correlation scales) of the K field is used to compute sample moments (e.g., of head, concentration). The ergodic hypothesis is employed to justify comparing these sample moments to the theoretical ensemble moments obtained analytically. But the ensemble moments also characterize the uncertainty about, e.g., head or concentration at a single unmeasured location within the aquifer represented by the simulation.

Analogous, we here use the ergodic hypothesis to postulate that the statistical sampling across the 150 well and 150 source areas simulated is representative of the ensemble moments (the stochastic management metrics) at an individual unmeasured well and its source area in the real-world aquifer represented. The 150 simulated wells and source areas are analogous to the single large realization in Rajaram (2002), since the K field is stationary.

In other words, we must assume ergodicity and stationarity to be able to equate the stochastic NPS management metrics obtained from across 150 samples (wells, source areas) to their ensemble properties. The ensemble properties in turn apply to any (unmeasured) well and its source area in the aquifer system. They characterize the uncertainty about these metrics at each (unmeasured) location (well, source area).

We propose to clarify this point in the manuscript (see below) and also refer to the histogram of the mean and variance of the K fields in supplementary material (Figure SM3, to be updated in the new version of the manuscript and shown below) showing stationarity in the moments of the K field, i.e., a very narrow range of values for the mean and variance, and therefore displaying that structural ergodicity can be assumed.

"Then, stochastic management metrics quantify both, the mean and variability of pollution levels across a large sample of production wells encountered over a basin as well as the expected value and uncertainty about pollution levels at an individual well. This is done by simulating stationary random fields (Figure SM3) and assuming ergodic conditions [e.g., Gelhar, 1993; Rajaram, 2002]." (line 122)

Reference: *Rajaram (2002), Perturbation theories for the estimation of macrodispersivities in heterogeneous aquifers, in Rao S. Govindaraju, Stochastic methods in subsurface contamination hydrology, p13-62.*

Gelhar, L. W. (1993), Stochastic subsurface hydrology: Englewood Cliffs, New Jersey, Prentice-Hall, 390 p.

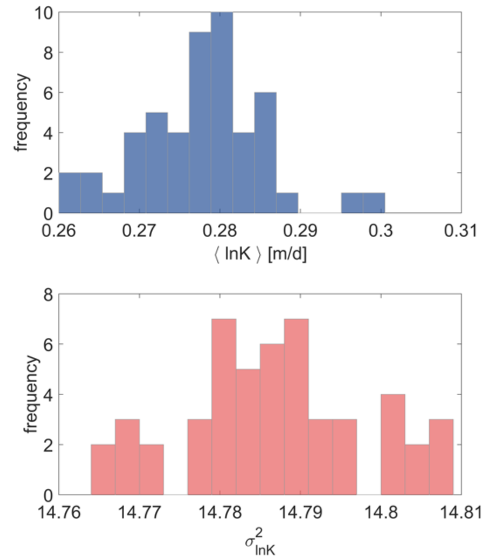

Figure SM3: Histogram of the mean (top) and variance (bottom) of the log-normal hydraulic conductivity.

- It would be interesting to see how the conclusions regarding recharge reported in this paper compare with the ones reported in the works of Rubin and Bellin (1994) WRR and Li and Graham (1999) WRR. These authors investigate the impact of recharge and its randomness on travel time pdfs.

Thank you for drawing our attention to these relevant papers. First, it might be interesting to note the differences between our simulation setup and the one used in Rubin and Bellin (1994) and Li and Graham (1999): The two aforementioned papers are (semi-) analytically analyzing 2D transport, with a point source and no pumping. Rubin and Bellin (1994) assumes uniform recharge and found that recharge increases longitudinal plume spreading. Li and Graham (1999) do account for spatial variability in recharge. In the chosen modeling conditions, the authors find that spatial variability in recharge further increases longitudinal spreading, and that uncertainty in the recharge spatial variability increases the uncertainty in solute concentrations.

On the other hand, we here simulate 3D transport, with non-point source transport, and significant pumping. Our results show little effect of recharge spatial variability (correlated to the top of the K-field) on travel times, while homogenization of recharge leads to increased uncertainty in well concentrations.

Results highlight that a potential superficial increase in lateral spreading is less (or non-) relevant in a 3D nonpoint source setting as indicated by our analysis of travel time statistics.

Concerning concentration statistics, the difference in outputs between Li and Graham (1999) and our work could indicate that decorrelated spatial variability of the recharge rate adds uncertainty, while a r-K correlation increases the conditioning of the flow field, which leads to decreased uncertainty. We recall that in our setting, the existence of a r-K correlation is a result of the explicit simulation of water flow in the unsaturated area.

In addition, considering three dimensions, as well as the presence of extraction wells adds some degree of complexity in transport and uncertainty propagation. Fully understanding these processes would require a significant effort of its own.

We propose to discuss these two points in a new version of the manuscript:

"Previously, Li and Graham (1998) investigated the impact of recharge spatial variability in a more theoretical and simplified 2D heterogeneous aquifer contaminated by a point source under non-pumping conditions. The work highlights that spatial variability in recharge increases spreading, especially in the transverse direction. In our 3D NPS setting, transverse spreading is less relevant (Figure 3) and we do not observe the increase in variability." (line 327)

"Li and Graham (1998) stochastically analyze the impact of spatially random recharge rate on transport in a 2D point source setting. Their work concluded that, for those conditions, large variability in – and therefore uncertainty about - recharge increases uncertainty in solute concentration. In our work, we observe the opposite. The difference may be partly due to the 3D non-point source transport, and partly caused by the implicit correlation between the hydraulic conductivity and the recharge rate in our scenarios, which may increase the conditioning the flow field that leads to the observed decrease of uncertainty relative to the homogenized scenario." (line 401)

- Line 460: "The results here confirm that..., but also put the macro-dispersive process. . .". I could not understand the meaning of this sentence. Please revise its structure. Thanks.

Thank you for pointing it out. This sentence has been changed to:

"The results presented here confirm this observation for the case of non-point source contaminations, but also highlight the generation of a quasi-macro-dispersive process through the (vertical) well mixing process." (line 460)