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Hydrology and Earth System Sciences
Discussions

# *Interactive comment on* "Stochastic inversion of sequential hydraulic tests for transient and highly permeable unconfined aquifer systems" *by* C.-F. Ni et al.

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We appreciate the valuable comments from anonymous referee #2 for our paper. These comments help us to improve the presentation of our study significantly. The following is the summary of our responses to the comments from referee #2.

Responses to the comments:

1.Introduction Paragraphs 1-2 Line 18: I am not sure whether Hernandez et al. (2006) developed a hydraulic tomography approach. Please check and conduct a thorough literature survey. Line 28: No, Neuman (1987) proposed the concept of hydraulic to-



mography first. However, the synthetic simulation by Yeh and Liu (2000) popularized the concept of hydraulic tomography. There are also other studies noted in Illman (2013) which reviewed the early to recent hydraulic tomography studies and perhaps you should look into this paper. I do not expect you to cite all the papers on hydraulic tomography listed in Illman (2013)'s paper but I think the key ones should be listed and reviewed in the introduction of your paper.

Response: Thank you for the comments. We will reorganize the introduction and add required references.

2.Paragraph 3 L14: I think that there are key laboratory and field hydraulic tomography studies that are missing here. L14: I am not sure whether Straface et al. (2011) conducted a hydraulic tomography survey. Please check carefully. Also, please note the studies of Berg and Illman (2011, 2013, 2014) in terms of field applications of the SSLE algorithm.

Response: The references will be added in the paragraph. Straface et al. (2007) conducted a hydraulic tomography survey. We will revise the text.

3.Paragraph 4: Line 17: You are examining the depth averaged case so why not talk about ln T instead of ln K?

Response: There are computation and programming considerations for using ln K instead of ln T in the modified model. In an unconfined aquifer system, the T value involves unknown head value (see equation (1) and (5)). We had inserted iteration loops in SSLE code to solve the nonlinear mean flow and adjoint state equations. To make the SSLE code to be modified as less as possible, we kept the original variable ln K in the SSLE code and let $T=Kh^*$ to solve the head (i.e., the h ) iteratively, where $h^*$ is the iteration head variable.

4.Optimization algorithm Paragraph 3: Line 3: What do you mean by "ready"? Line 11: replace "head differences" with residual heads based on the previous sentence.

Response: The sentences will be rephrased to make it clear. Thanks for the comments.

5.Sensitivity estimations for covariance matrices Paragraph 1 Line 15: Are all of these details necessary to be given in this paper when the details are provided in previous papers on this topic? Please think about putting this into an appendix or dropping it unless there is something new that should be presented.

Response: There are additional terms in the adjoint state equation and sensitivity equations. Previous investigations did not involve the derivations of these equations for deep-averaged, unconfined, and transient aquifer systems. We will improve the presentation.

6.5.1 Model description Paragraph 2 Line 14: Not sure that Figure 2 is a conceptual model. It simply shows the model domain and the different boundary conditions. It also shows the pumping and observation well locations. Can you combine this figure with Figure 1?

Response: In Fig. 2 we showed the numerical conditions for the synthetic example. The sentences will be rephrased to clearly present the conditions of the model.

7.5.2 Results and discussion of the numerical example Paragraph 2: Line 21: I am not sure whether I understand what you are trying to do here. Are you doing a steady state simulation and comparing the resulting ln K estimation to the transient case? Line 23: Perhaps you should include a scatterplot to compare the two K estimates (one from steady state and one from transient).

Response: That is correct. We did a comparison. This paragraph will be removed from the paper because a systematical test is required to carry out a strong conclusion. We have here is only a synthetic case with one sampling strategy.

8.Paragraph 3: Line 3: (Figure 5) Can you please explain this plot a little better? Are these calibration plots or are they validation plots? Also I would recommend Plotting these in terms of drawdowns. In addition, I was not clear whether these are plots for



each pumping test or results from tomography (calibration) by adding 1 to 5 pumping tests to the analysis?

Response: This is a calibration plot. Thank you for the suggestion. We will modify the figure and revise the text.

9.Line 11: So you had to include 14 or so conditioning points in the inverse modeling effort. I think the previous studies by Yeh and his colleagues have not had to do this. Is there a reason why this is the case?

Response: This is not a required condition. We will make it clear in the text.

10.Line 18: This is a new finding. Reading Yeh and his colleagues' past papers, it looks like the variances are higher away from where there are data points regardless of whether the boundary is close or not. Can you provide an explanation of why you see these results with lower variance along the top and bottom boundaries?

Response: Here the error variances along constant head boundaries show one order of magnitude smaller than those away from conditioning points. The error variances at well with known K values are zeros. The legends for these figures may cause misunderstanding. We will revise the figures for better presentation. The K and h variations are two sources to contribute the cokriging error variances in the modeling area. For constant head boundary conditions, the head values are deterministically assigned, implying that the head variations at constant head boundaries should be zero. Such zero head variance values can lead to lower cokriging error variance values along the top and bottom boundaries. Further numerical experiments are required to clarify the weightings of head and K variations to contribute the cokriging error variances.

11.6.1 Site description Paragraph 1: Line 18: What is the K of the Cholan formation and how does this compare to the K of the alluvium? Please be more specific so that you can better justify treating the bottom boundary as no flow.

Response: The K for the Cholan formation is from 10-3 to 10-7 m/day. We will add the information for the site description.

12.Paragraph 2: Line 25: Please be more precise about how long the screened intervals are for both the injection and observation wells. Please consider including a table of the well locations and screen lengths including the elevation of the well.

Response: Thanks for the suggestion. In this study the wells were fully penetrated for both injection and monitoring wells. The differences are the diameters of the wells. We will provide detailed information about the wells in the text.

13.Paragraph 3: Line 9: How did you monitor the head in the injection well? Line 14: Why did you not include the heads at the injection well? For example, Illman et al. (2008) did not include head data from the pumped location because of skin effects and other potential nonlinear effects (e.g., well losses due to inertial flow, etc.).

Response: We used the pressure sensor GE DRUCK to monitor the pressure changes at 5 injection wells. This information will be added in the text. During the injection tests, we will obtain high head fluctuations and quick head changes at injection wells (see figure 9). Such observations may be influenced by well bore effect. We did not have enough information to judge if the head observations at injection wells can be used for the parameter inversion. We will address this point in the text.

14.6.3 Parameter estimations Paragraph 1 Line 30: You mention that the model did not include any K and Sy observations. My understanding is that SSLE requires at least one observation to begin the estimation process. Please clarify.

Response: That is correct. We do have one observation at lower left corner of the modeling area. We will address this in the text.

15.Paragraph 2: Line 18: How do these estimates compare to what you know about the geology? Are the estimated K values consistent with K estimated from grain size analysis or other local estimates such as from slug tests?

Response: We did have two slug test data for two of the injection wells. The average K



value based on the two slug tests is 50.2 m/day. This value is the initial mean K value for our field-scale inversion.

16.Line 19: I would think that these Sy values are on the low end given that Sy = saturated water content - residual water content. Can you comment on this further?

Response: What we knew is that the Sy value should be close to the effective porosity of an unconfined aquifer. However, for realistic problems the non-disturbed measurements of porosity values in wells are very difficult.

17.Line 25: Do you expect a similar cokriging error variance distribution for K and Sy? And why is the error larger for Sy on the right side of Figure 11b while there is a bull's eye on the left side. Can you please provide the reader with some insights on this distribution?

Response: We don't expect a similar cokriging error variance distribution for K and Sy. Unlike the synthetic case, there is no conditioning point in the modeling area. The patterns of the error variance distributions for K and Sy are solely depending on the head observations. We can focus on the descriptions of estimation results and the error variances. There are too many factors involved in the real data.

18.6.4 Boundary effect on parameter estimations Paragraph 1 Line 9: I do not think the first part of this sentence is necessary given that you say the same in the previous paragraph. It is repetitive.

Response: Thanks for the comment. We will revise the text.

19.Paragraph 2: Line 21: This analysis is interesting and kind of important. It shows that hydraulic tomography may provide information on K and Sy heterogeneity beyond the vicinity of the well field. This contradicts with the findings of Bohling and Butler (2010) and I think you should state this here. Also I recommend you plotting the error variance distributions for each case. Finally, you should refer to Sun et al (2013) and discuss the implications of how tomography may be able to map regions beyond the immediate vicinity of the wells.

Response: Thanks for the suggestion. We will revise the text and address these points.

20.7. Conclusions Paragraph 1 Line 20: I suppose this is a form of sequential cokriging interpolation but I believe SSLE is more than cokriging. To avoid confusion in the literature, I suggest referring this approach as SSLE.

Response: Thanks. We will follow the suggestion.

21.Paragraph 2: Line 9: The boundary condition effect on the estimated K. I am a little puzzled here because other applications of SSLE did not result in lower variances of K at the constant head boundaries. What you are fixing is the boundary heads and not K so I do not see any reason why the variance should approach zero. I would think quite the contrary that away from available data points, the variance estimates would be larger even near boundaries. This issue needs further clarification and investigation.

Response: Here the error variances along constant head boundaries show one order of magnitude smaller than those away from conditioning points. We will revise the figures for better presentation. We will make the discussion of error variances and constant head boundaries specifically. This issue indeed requires further clarification and investigation.

References:

Berg, S. J. andW. A. Illman (2011b), Three-dimensional transient hydraulic tomography in a highly heterogeneous glaciofluvial aquifer-aquitard system, Water Resour. Res., 47, W10507, doi:10.1029/2011WR010616.

Berg, S. J. and W. A. Illman (2013), Field study of subsurface heterogeneity with steady state hydraulic tomography, Ground Water, 51(1), 29-40, DOI: 10.1111/j.1745-6584.2012.00914.x.

Berg, S. J. and W. A. Illman (2014), Comparison of hydraulic tomographywith traditional



methods at a highly heterogeneous site, Ground Water, doi:10.1111/gwat.12159, Article published online.

Bohling, G.C., and J.J. Butler Jr. (2010). Inherent limitations of hydraulic tomography. Ground Water 48, no. 6: 809–824.

Cardiff, M., and W. Barrash (2011), 3-D transient hydraulic tomography in unconfined aquifers with fast drainage response, Water Resour. Res., 47, W12518, doi:10.1029/2010WR010367.

Illman, W. A., Craig, A. J., and Liu, X.: Practical issues in imaging hydraulic conductivity through hydraulic tomography, Ground Water, 46, 120–132, 2008.

Illman, W. A. (2013), Hydraulic tomography offers improved imaging of heterogeneity in fractured rocks, Ground Water, doi: 10.1111/gwat.12119.

Mao, D., T.-C. J. Yeh, L. Wan, J.-C. Wen, W. Lu, C.-H. Lee, and K.-C. Hsu (2013), Joint interpretation of sequential pumping tests in unconfined aquifers, Water Resour. Res., 49, 1782–1796, doi:10.1002/wrcr.20129.

Neuman, S.P. (1987). Stochastic continuum representation of fractured rock permeability as an alternative to the REV and fracture network concepts. In Rock Mechanics: Proceedings of the 28th US Symposium, Tucson, AZ, eds. I.W. Farmer, J.J.K. Daemen, C.S. Desai, C.E. Glass, and S.P. Neuman, 533–561. Rotterdam, The Netherlands: A.A. Balkema, 1240. (Also in Groundwater Flow and Quality Modelling, eds. E. Custodio,A. Gurgui, and J.B. Lobo Ferreira, 331–362. NATO ASI Series C, 224. Dordrecht, Holland: D. Reidel, 843, 1988.)

Straface, S., Yeh, T., Zhu, J., Troisi, S., and Lee, C. (2007). Sequential aquifer tests at a well field, Montalto Uffugo Scalo, Italy, Water Resour. Res., 43, W07432, doi:10.1029/2006WR005287, 2007.

Straface, S., Chidichimo, F., Rizzo, E., Riva, M., Barrash, W., Revil, A., Cardiff, M., and Guadagnini, A.(2011). Joint inversion of steady-state hydrologic and self-potential data for 3-D hydraulic conductivity distribution at the Boise Hydrogeophysical Research Site, J. Hydrol., 407, 115–128.

Sun, R., T.-C. J. Yeh, D. Mao, M. Jin, W. Lu, and Y. Hao (2013), A temporal sampling strategy for hydraulic tomography analysis, Water Resour. Res., 49, doi:10.1002/wrcr.20337.

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