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Hydrology and Earth System Sciences
Discussions

Interactive comment on "Estimation of heterogeneous aquifer parameters using centralized and decentralized fusion of hydraulic tomography data from multiple pumping tests" *by* A. H. Alzraiee et. al

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RESPONSE TO COMMENTS FROM REVIEWER # 3

Note: We use text with black color for reviewer comments (RC), blue color for author

comments (AC), and red color for modified text.

Response to General comments

[RC#1] The authors develop and test an EnKF approach which incorporates temporal moments of drawdown data in a centralized and decentralized manner to estimate the hydraulic conductivity and specific storage of a 2D synthetic aquifer. Temporal moments are utilized to overcome the computational burden associated using the full parabolic equation for inverse modeling. A novel localized fusion algorithm is implemented to further save on the computational effort which I thought was clever but perhaps the authors may consider comparing this search radius approach to the full inversion case because features in the far field could have impacts in the near field (I am thinking of strongly heterogeneous porous media and in particular fractured rocks). However, this demonstration is up to the authors as they have already done a significant amount of work. The algorithm is also expanded to estimate the geostatistical parameters and some useful conclusions are drawn about the estimation of these parameters. Overall, I thought that the study was well thought out and the paper is generally well written although minor edits are necessary.

[AC#1] [We would like to thank Reviewer #3 for his/her valuable comments and constructive suggestions, which help improve our paper. All comments were addressed in this response letter and in the manuscript. Regarding the full inversion of hydraulic properties using Millman's Fusion, tests we have not presented in the paper have shown that, for the problem at hand, increasing the radius of influence beyond 50 meters does not produce a significant improvement in results, while it requires an exponentially increasing computer effort.]

[RC#2] I also think that some efforts are needed to distinguish this study from another similar HT study based on EnKF by Schöniger et al. (2012). This will simply require some additional explanations. I think that the conclusions are substantiated through the numerical study; therefore I recommend publication of the manuscript after minor revisions.

[AC#2][We would like to point out that the only similarity between our work and that of Schöniger et al.(2012) et al. (2012) lies in the use of the EnKF as an inversion processor, and thus we cited and discussed Schöniger et al.(2012) work in this context. Note, however, that Schöniger et al.(2012) do not address issues related with CF and DF approaches, and they do not use temporal moments in their HT analyses.]

Response to Specific comments

[RC#3] Comments (P?L? refers to page and line numbers of the PDF page)

[AC#3] No Reply is required.

[RC#4] Title: suggest removing from multiple pumping tests; hydraulic tomography already Implies the use of multiple pumping tests for inverse modeling.

[AC#4] [We made the suggested changes to the title.]

[RC#5] P3L16: Pumping and slug tests are not classical examples of inverse methods. The analyses using type curves or straight line methods are. Please pay attention to your writing throughout the manuscript.

[AC#5] [We agree with the reviewer. The text is modified as follows: "Analyses of hydraulic head data resulting from pumping tests and slug tests using type-curves techniques are classic examples of inverse methods used to infer hydraulic properties of porous media".]

[RC#6] P4L11: Please cite the various temporal moment analysis of hydraulic tomography conducted (e.g., Zhu and Yeh, 2006; Schöniger et al., 2012).

[AC#6] [We cited the work of Zhu and Yeh, 2006 when we discuss the use of temporal moments in HT in the introduction in paragraph number 10, and we cited Schöniger et al., 2012 in paragraph number 5 in the introduction as an example of using the EnKF for hydraulic conductivity characterization. However, we would like to point out that Schöniger et al., et al. (2012) did not use temporal moments in their work.]

[RC#7] P4L14: In talking about 3D settings, you should mention the work done by Illman et al. (2009) and Berg and Illman (2011) with the latter you already cite. You may also consider citing Berg and Illman (2013, 2014) for additional examples of 3D studies.

[AC#7] [We added the citations suggested by the reviewer].

[RC#8] P4L20: Here you should perhaps cite the work of Illman et al. (2012) who found that predictions of solute transport were better with estimates from HT surveys in comparison to traditional geostatistical analysis (i.e., kriging) and effective parameters (effective conductivity and macrodispersivity).

[AC#8] [Comments and citation have been added to the manuscript. The modified text is read as: " Similar results reported by Illman et al. (2012) revealed that predictions of solute transport were better characterized with estimates from HT surveys in comparison to traditional geostatistical analysis and effective parameters."]

[RC#9] P5L3: While the nonuniqueness issue is true for all inverse methods, it was really unfortunate that Bohling and Butler (2010) was published without the necessary caveats. In particular, Bohling and Butler (2010) generalized their conclusions to all HT studies without considering the merits of inversion methods other than their own. Therefore, I think you should add the statement "based on their pilot point inverse method" after "reliability of HT estimates, and".

[AC#9][We agree with the reviewer and we made the changes suggested by the reviewer. The modified text reads as this: "With respect to the latter, Bohling and Butler (2010) caution practicing hydrologists against "overselling" the reliability of HT estimates based on their pilot point inverse method, and argue that some form of regularization is typically necessary to reduce uncertainties associated with the nonuniqueness effect."]

[RC#10] P6L7: Please carefully discuss the differences of your approach with that of Schoniger et al. (2012) in this paragraph.

[AC#10][Please refer to our comments AC#2 and AC#6.]

[RC#11] P8L11: I do not think one needs to use a lot of drawdown data for inverse modeling. The key is to capture the salient features of the drawdown curves.

[AC#11][In general, HT experiments result in large amount of data. This situation was described as "data-overload" problem by Zhu and Yeh(2005). We agree with the reviewer that it is possible to invert only a subset of the HT data. However, there is a need to develop criteria that discard some data and keep others; in this work, we did not tackle this issue. In our opinion, there are several factors that make inversion of a large data set a necessary step of HT. For example, estimating the spatial variability of a large site obviously needs more pumping tests at different locations and a dense system of observation wells. In fact, there is a possibility to reduce the temporal frequency of inverted data when continuous extractions is forced; however, for drawdown hydrographs resulting from variable pumping rates, reducing the temporal frequency of data might not be a trivial procedures. Another reason that may contribute to the data overload problem is when the temporal frequency of data collection is increased as a result of the timing of data selection, which should be different from one monitoring well to another, since there is a distance-dependent "delay" between the change in pumping rate at the pumping well and the variation of head at each observation well. In our tests we did not consider this "optimal" sampling but elected to use a uniform somewhat "averaged" temporal frequency, which we expect to have a negligible effect on the calculation of the data of interest, that is m_0 and m_1.]

[RC#12] P11L19: Schöniger et al (2012) had to apply nonlinear, monotonic transformations to the observed states (head), rendering them Gaussian. Do you have to do something similar to make your approach work? You should say a few words here and perhaps in more details in the discussion section.

[AC#12][The EnKF is known to provide an optimal solution in the case of linear processes with state variables that are both jointly and marginally gaussian and data charaterized by gaussian noise. In our case, none of these hypotheses is met. Preliminary tests we conducted, whose results have not been included in our manuscript,

have shown that in this case transformations such as the normal score transform (NST) proposed by Schoniger et al. (2012) do not necessarily improve the solution of the inverse problem since they can at most render state variables marginally gaussian, but do very little with respect to joint gaussianity, and may lead to a significant loss of the spatial autocorrelation of state variables, and the cross-correlation between state variables and parameters.]

[RC#13]P12L12: Is there a way to include other covariance functions? If so you should state it here.

[AC#13][Yes, any covariance function could be used. We modified the text to show that. The modified text read as:" This choice is somewhat arbitrary and other covariance functions might be used to describe the spatial correlation of random field without altering the general inversion methodology."

[RC#14] P12L20: So this step should be very computationally intensive especially for 3D cases. How does your approach compare to other inverse methods such as pilot points (Vesselinov et al 2001b and others), SSLE (Yeh and Liu, 2000; Zhu and Yeh, 2005), etc. Perhaps this point should be addressed in the introduction and in the discussion section.

[AC#14][This is a very good question, whose answer is not quite immediate but would require an ad hoc comparison between our GMF-based DF approach and the methods cited by the reviewer. While this comparison is outside the scope of our work, it may be addressed in future reserach effort. It is important however to note that the GMF is not an inversion tool in itself, but can used it to merge multiple estimates that could be made by any inversion algorithm, such as the EnKF, the pilot-point method, or the

SSLE.]

[RC#15] P23L7: Table 4 is nice but I would also like to see scatterplots of each case to get a pictorial representation of the fit quality.

[AC#15][In general, we agree with the reviewer that visual comparison would be faster and more effective. However, for the sake of space we elected to keep the number of scatter plots to a minimum . Indeed, for the CF method alone, 10 figures would be necessary (5 for Y and 5 for Z). As many figure would be necessary for the DF method. In addition, we believe that the relatively minor differences among r values in all cases would make the visual comparison of scatter plots rather difficult.]

[RC#16] P24L16: Are you estimating K and Ss separately? How about the simultaneous estimation of K and Ss? This should perhaps be added as a new case.

[AC#16][Estimating K and Ss jointly is implicitly included in Table 1. To illustrate, the simultaneous estimation of K and Ss is achieved using a formulation of Xf equal to Xf = [Y Z M0 M1]. Since Y and Z are uncorrelated this formulation can be split into the two formulations Xf_1 = [Y M0 M1] or Xf_2 = [Z M0 M1] , where the first formulation Xf_1 is the same as Formulation C, and the second formulation Xf_2 can be reduced to Xf_2 = [Z M1] since M0 does not depend on by Z according to equation 7 . This means that Xf_2 is equivalent to D] .

[RC#17] P25L20: “3600 measurements per single pumping test”. However, no one ever uses all the data for transient inversions so this is kind of misleading, I think. Only a few points from the drawdown curve are typically utilized.

[AC#17] [We have addressed this comments in AC#11. We would like to add that in this synthetic example, using large number of measurements is necessary to accurately calculate the integral in equation 4.]

[RC#18] P27L17: “what” field?

[AC#18] [We modified the text to clarify which field we mean. The modified text reads as] “ Indeed, only estimates of the hydraulic parameter field and the covariances are required."

[RC#19] P27L26: replace “priorly known” with “a priori”.

[AC#19][This section has been removed as explained in previous comments.]

[RC#20] P28L5: Note that the work of Yeh and Liu (2000) found that the choice of correlation lengths and variance did not influence their estimates. Perhaps you should say a few words about this study.

[AC#20][This section has been removed as explained in previous comments.]

[RC#21] P29L16: replace “stationary” with “stationarity”.

[AC#21][This section has been removed as explained in previous comments.]