Reply to Reviewer #2

We thank the reviewer for the useful feedback.

All comments from the reviewer are repeated in italic face, our response is thereafter in regular face. A proposal for new text is indented.

General comments

This paper tackles a very relevant topic. It presents a method to update layer thicknesses and hydraulic conductivities of geological layers from a geological model by using calibrated hydraulic conductivities from groundwater flow models of aquifers or aquitards that consist of some of the geological layers from the geological model. This is very relevant since geological models and groundwater flow models are often both available in a certain area. Both types of models have uncertainties. Typically groundwater flow models use model thicknesses and parameter values from the geological models, but this paper shows that also output from the groundwater flow model might improve the geological model. As the borehole data that is used to build the geological model is also uncertain, the authors investigate whether this uncertainty can be reduced by using results from a calibrated groundwater model. I think this is a very interesting research question.

As the approach is unconventional and as the method consists of many different substeps, it is not easy to understand all details of the methodology during the first reading. I suggest the authors add a flowchart showing all the different steps in the methodology.
R2.1 We agree that this will improve the readability of the paper. We will add an introductory subsection to section 2 where this flowchart will be explained. In the appropriate sections we will refer to this flowchart.
Please find the draft version of this flowchart and the introductory text at the end of this reply.

I also suggest to replace the term "groundwater model" by "groundwater flow model" so that the difference between the hydrogeological model and the groundwater flow model is clear since this is essential for a good comprehension of the paper.
R2.2 This is a good suggestion, we will apply this throughout the paper.

It might also be helpful if the authors provide some definitions in the beginning of the paper about how they define hydrogeological model, groundwater model, lithological layer, model layer, aquifer, ... and what are the differences between all these terms.
R2.3 We will add these definitions to the introduction. Concerning this point, your remarks of point R2.1, and the remarks of reviewer 1, we will rewrite the introduction of the paper.
Please find a draft version of this new introduction at the end of the reply to reviewer 1.

The paper is written in good quality English.

Specific comments

- Page 4192, Line 10: which parameters?
R2.4 In fact, we assume that all calibrated parameter values represent the truth, but in this context we only need the transmissivity and the vertical resistance.
We will rephrase the sentence to:

> Subsequently, the calibrated ~~parameter values of the groundwater flow model are assumed to be the truth and, from these parameters the calibrated~~ transmissivity and vertical resistance are used to find the most likely combination of layer thicknesses and hydraulic conductivities for the lithological layers making up the aquifer or aquitard.

- Page 4196: we assume that the PDF of the hydraulic conductivity for a given litholayer does not change in space. This is an important assumption. Can the method be extended without this assump-

tion? This might be very interesting. I would like to see some discussion on this.
R2.5 In the discussion section, page 4208, line 10 to 19, we discuss the point of spatial variability of the PDF of the hydraulic conductivity. There, we state that it is not unlikely that this distribution is spatially varying. At this moment, we don't have information available about spatial variability of these PDFs, therefore we had to make this assumption. Application of the proposed method to a large area might yield information about this possible variability, but we left this for future research. If the spatial variability of the PDFs is known a priori, there is no problem in the method to replace a constant PDF of K_l by a spatial variable PDF $K_l(u)$. The algorithm of finding the most likely parameter values in a grid cell will be exactly the same.
We will replace this part of the conclusions with:

> In the REGIS database the a priori probability distributions of the vertical conductivity, for a given litho-class, are assumed location independent. R2.5 However, this is not a limitation of the proposed method but of the available data. It is not unlikely that the a priori distribution of the vertical conductivity of a litho-class is spatially varying. If the spatial variability of the probability distributions is known, this can be used in the described method. In future research, this method can be applied to find this spatial variability of the probability distributions of the conductivities.
> The posterior distributions of the two most important litho-classes show much less variability than the corresponding prior distributions do. This reduction of uncertainty can be expected as additional knowledge is added using results from a calibrated groundwater R2.2 flow model. However, at this point this is yet not a reason to update the prior distribution in the REGIS database, because the posterior distribution is based on a small study area, while the prior distribution is based on data from the whole data base. R2.5 ~~Moreover, it is not unlikely that the a priori distribution of the vertical conductivity of a litho-class is spatially varying. Subsequent application of this method to a larger area will give more certainty about this.~~

- If I understand correctly the optimization of the thickness and hydraulic conductivitiy is done per grid block. Is it possible that neighboring grid block are assigned very different thicknesses and hydraulic conductivity leading to big or unrealistic jumps in layer thicknesses or hydraulic conductivity?
R2.6 The search for the most likely parameter values is indeed performed per grid block. Nevertheless, it is very unlikely that neighboring grid blocks are assigned very different values for the same parameter. The PDFs of the layer thicknesses are obtained by kriging interpolation, which has a smoothing effect. Thus, PDFs of the layer thickness in adjacent grid cells are quite similar. The used PDFs of the conductivities is everywhere the same within a litho-class. When the PDFs in adjacent grid cells are quite similar, the most likely parameters will be quite similar too. Herewith, the main source of lateral variability is the calibrated parameter field. The hydraulic response of the groundwater flow model, and the observations, may justify high variable calibrated parameter fields. Since we stated that the calibrated values are considered to be the truth, variability of this parameter should be reflected in the results.
In the results of our calculations, we haven't discovered parameter variability on short distance which could be caused by applying the method on single grid blocks instead of taking the spatial correlation into account.

- 2.4 Layer thickness uncertainty: The roundoff error is considered as the layer thickness uncertainty. Is misclassification of a layer by the geologist describing the borehole material not a bigger error than the roundoff error? Is this considered?
R2.7 We agree that layer thickness uncertainty is not the only source of uncertainty in the hydrogeological and groundwater flow models. In section 2.4, page 4200, line 7 to 15, we assume that there is a relation between the roundoff error and the accuracy of the layer descriptions. So the roundoff error can be seen as related to the accuracy of the description, but it is certainly not the ultimate solu-

tion. Interpretation of the borehole material and classification of the borehole descriptions is certainly prone to errors. It is even expected that this kind of errors may be relatively large. But we think that it is quite difficult to quantify these errors and use them in the data analysis.
However, when the interpretation of the borehole data does not agree with the results of the calibrated groundwater flow model, the proposed method will generate unlikely parameter values. This may indicate a discrepancy between the hydrogeological model and the groundwater flow model, and a source of error may be located.

- The variogram models are tabulated but no graphs are shown showing the correspondence between experimental and modeled variograms. This would be interesting to judge the quality of the variogram models.
R2.8 Since this study aims to develop a new method and the current results are not meant to update the REGIS data base, we decided not to present the experimental variograms. Nevertheless, we agree that it is very important to have that information to judge the validity of an update of a data base. We propose to add the experimental variograms as supplementary material to this paper. Please find a draft version of the graphs at the end of this reply.

- Can the uncertainty of the calibrated values be incorporated in the method? From the calibration of the groundwater flow model by PEST for example, you can get uncertainty bounds of the optimized parameters. This information could be used to decide on a trade-off between the flow model results or borehole information based on their accuracy. Could this be possible? Please provide some discussion on this.
R2.9 In the discussion, page 4209, line 12, we mentioned this subject. We agree that this really would be a valuable extension to the proposed method, but we left the implementation for future research. We propose to extend the current text as follows:

> As with the assignment of litho-classes, also the calibrated vertical resistance of the groundwater R2.2 flow model is regarded as perfectly known. A valuable extension to the presented method is to account for uncertainty of the calibration results. R2.9 When the calibration method is able to provide probability distributions of the calibrated parameters, these distributions can be used instead of the scalar values in the presented method. It is possible to extend the current method to account for these uncertain calibrated data. Herewith, the most likely parameter values will be probability distributions instead of scalar values. An advantage of this modification is that the value of the results can be judged. Furthermore, results from different calibrated groundwater flow models in the same area can be compared.

Introduction to section 2

The methodology described in this section consists of several steps. A flowchart is given in Fig. 1 which shows the four processing steps and the three sources of input data. The core part of the method is step 4 (Sec. 2.1). Herein, for each grid cell the joint distribution with the marginal distributions D_l and K_l are defined. From this joint distribution, the most likely parameter values (layer thickness and conductivity) of all litho-classes are found by using the calibrated vertical resistance (c_m) of a groundwater flow model.

To be able to build this joint distribution, the marginal distributions need to be known. In the REGIS system, the distributions of the conductivities are defined for each litho-class. However, no information about the uncertainty of the layer thicknesses is readily available. Therefore, in step 1 (Sec. 2.4) a PDF is assigned to each defined litho-layer from the interpreted borehole data from REGIS. In step 2 (Sec. 2.3) these data are aggregated to one PDF of the total thickness of each litho-class at each borehole. In step 3 (Sec. 2.2), a kriging interpolation is performed, using the result of step 2 as observations. This yields a PDF for the thickness of each litho-class at each grid cell. The resolution of this grid is equal to the resolution of the calibrated groundwater flow model.

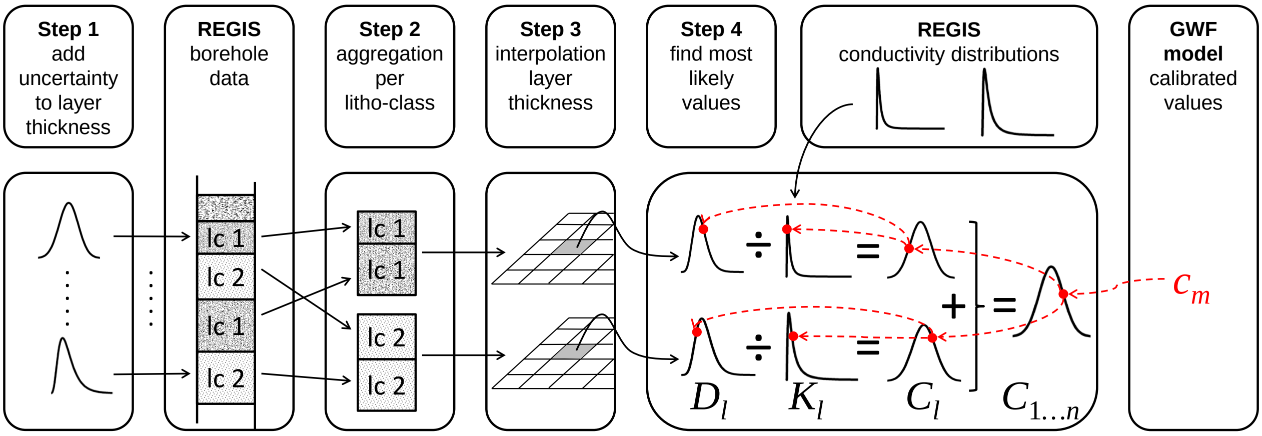
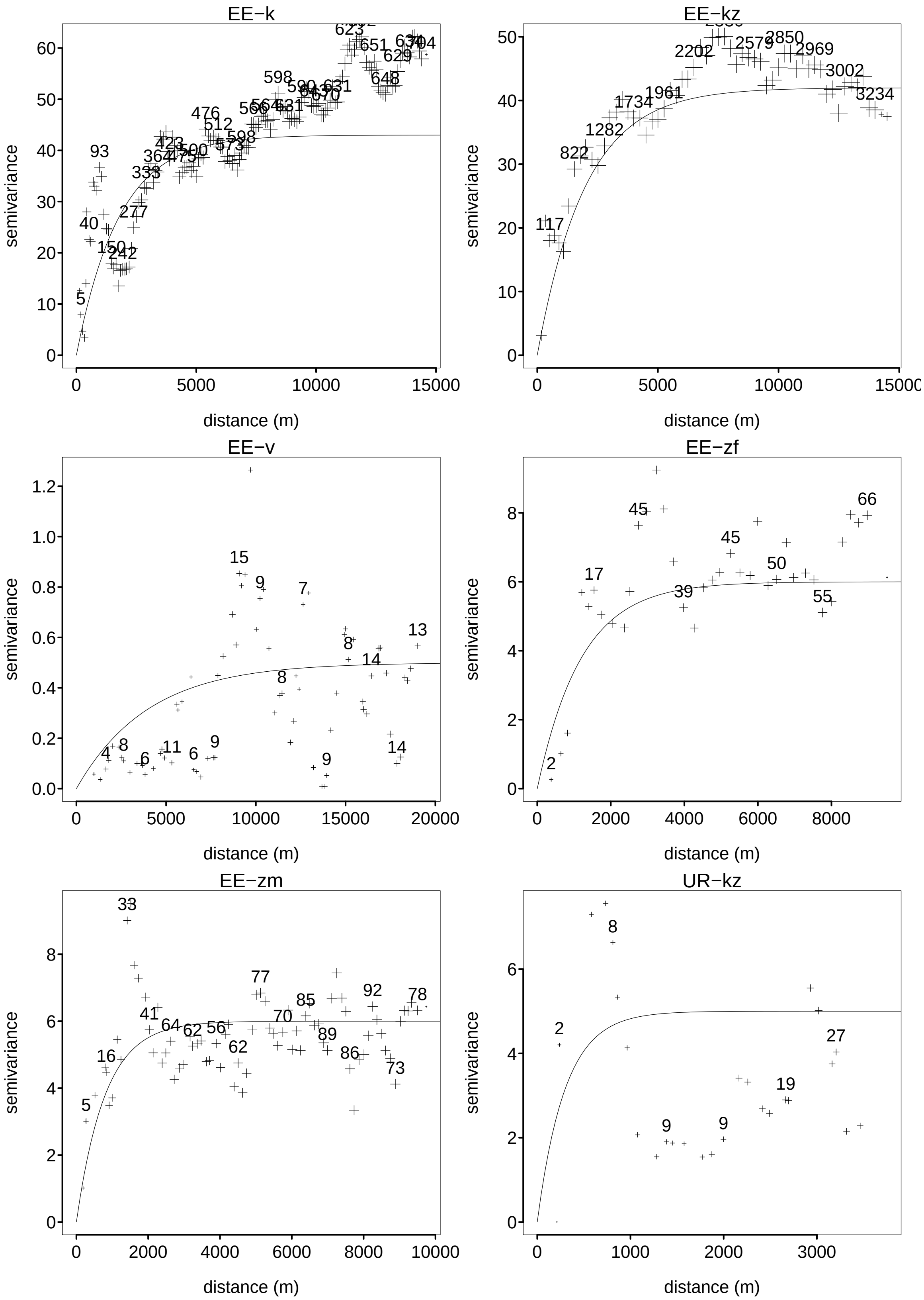


Figure 1: Flowchart of the method as described in Sec. 2. The descriptions of step 1, 2, 3 and 4 are found in Secs. 2.4, 2.3, 2.2 and 2.1, respectively. This chart shows an example with two litho-classes (lc 1 and lc 2) in one aquitard.

Variogram models



Experimental variograms and variogram models for each litho-class as used in this paper. The size of the plus signs is proportional to the number of observation pairs used to calculate the semivariance. At every fifth point the number of pairs is written.