

Reply to Reviewer #1

We thank the reviewer for putting the effort in reviewing our paper.

All comments from the reviewer are repeated in italic face, our response is thereafter in regular face.

The current manuscript needs to be thoroughly rewritten before it can be considered for publication. I have not been able to understand neither the objective of the paper, the methods, the example nor the conclusions. It lacks rigor (in too many places) and clarity in presentation. I do not doubt that there may be some value in the research in which it is based, but such value is impossible to be extracted from this, apparently hastily written, manuscript.

R1.1 To clarify the objective of the paper, the introduction is rewritten. Please find a draft version attached.

Reviewer 2 has suggested to add a flowchart for a better overview of the paper. Please find it attached to the reply to reviewer 2.

We hope this contributes to a better understanding of the objectives of the paper.

New introduction

Characterization and modeling of the subsurface is practiced by geologists as well as hydrologists. In many cases the communication about the subsurface properties is only one way, from the geologist towards the hydrologist. In this study we explored possibilities for feed back, from the hydrologist towards the geologist. More specific, we developed a procedure to improve the hydrogeological model describing subsoil lithological and hydraulic properties using the results from a calibrated groundwater flow model. Here, a groundwater model is a numerical model that is used to calculate groundwater hydraulic heads and groundwater flow. In this context, hydrogeological models are the result of a geological interpretation and modeling process, including a number of steps such as core description, spatial interpolation and up-scaling. Identification of deposits with distinct hydraulic properties, at observed and unobserved locations, is vital for the creation of a hydrogeological model (e.g., Nilsson et al., 2007; Rogiers et al., 2014). Based on geological and hydraulic properties of the sediments, model layers are recognized. Typically, the model layers of hydrogeological and groundwater flow models are divided into high conductivity (aquifers) and low conductivity layers (aquitards). Usually, the hydrogeological model serves as the basis of the subsurface description of the groundwater flow model. We focus on a subsurface consisting of unconsolidated sediments.

The model layers of the hydrogeological models consist of litho-layers in three spatial dimensions. Here, a litho-layer is a consecutive vertical part of the subsoil with a uniform litho-class. Herein, the litho-class is defined by the type of lithology of the deposits and the geological formation it belongs to, e.g. fine sand deposits of the Eem Formation. The thickness of the litho-layers most often ranges from a few centimeters to meters. Important hydraulic properties attached to the litho-layers are the horizontal and vertical conductivity and the storage coefficient. In this study we concentrate on the vertical conductivity (k_v), but the developed procedure is also valid for other hydraulic properties.

A hydrogeological model represents the appearance of the litho-layers at a specified scale. Due to the geological modeling process, the hydrogeological model is subject to uncertainty. In this study we used the Dutch regional hydrogeological information system REGIS (Vernes et al., 2005; Vernes and van Doorn, 2006), which scale is comparable to a horizontal grid size of $100\text{m} \times 100\text{m}$. REGIS is able to provide the following information to the groundwater modeler: the occurrence of a particular litho-layer within each model layer, and the probability distribution of the horizontal and vertical conductivity of each litho-class.

The aim of the procedure described in this paper is to improve the hydrogeological model REGIS, using the calibration results of a groundwater flow model that uses REGIS hydrogeological data as input.

Many groundwater flow models consist of a limited number of aquifers and aquitards. In the remainder of this paper, aquifers and aquitards are called model layers. In these model layers, several litho-layers are pooled together. The grid size of the AZURE model (de Lange and Borren, 2014) that we used here to demonstrate the feed back procedure, is comparable to the scale of hydrogeological model REGIS. Groundwater flow models are calibrated by adjusting the values for the transmissivity and the vertical resistance (or conductance) of the model layers in order to reproduce the observed groundwater heads. There is a huge number of papers about calibration procedures (e.g., Zimmerman et al., 1998; Valstar et al., 2004; Carrera et al., 2005; Hendricks Franssen et al., 2009; Hoteit et al., 2012), but this is outside the scope of our study. Although we realize that the calibration might be influenced by misconceptions and sparsely distributed data, and therefore is subject to uncertainty itself, for now we assume that the calibrated aquifer or aquitard properties represent the true parameter values at the applied scale.

As stated, in this paper we concentrate on the vertical conductivity (k_v) of aquitards only. Thus, central in the feed back procedure is the question: how can we use the calibrated vertical resistance per grid

block to get a better estimate of the expected thickness and the vertical conductance of each individual litho-layer, and how can we reduce the associated uncertainty. So the rationale is not to improve the groundwater flow model, but improve the hydrogeological model, which is beneficial for future use of the hydrogeological information system. In addition, the feed back procedure facilitates the discussion between geologists and hydrologist. On the one hand, hydrologists might accept calibrated values which are unrealistic from geological point of view, and on the other hand, calibrated values from the groundwater flow model might show inconsistencies in the subsurface characterization.

The upscaling of the borehole data to data representative for hydrogeological layers for numerical model blocks is a process of major importance and has to be applied carefully. A vast amount of literature is available on this topic (e.g., Dagan, 1986; Nøtinger et al., 2005; Sanchez-Vila et al., 2006; Fiori et al., 2011). Since the proposed method makes use of an available hydrogeological and groundwater flow model, and the results are valid at the model scale, this upscaling is no part of the method. Therefore, upscaling will not be discussed in this paper.

This paper is organized as follows. In Sect. 2 the methodology is described, which, in this paper, focuses on the resistance of aquitards. In Sect. 3 the study area and the data used are presented. The results are presented in Sect. 4. In Sect. 5 the method is discussed and conclusions are drawn.

References

- Carrera, J., Alcolea, A., Medina, A., Hidalgo, J., and Slooten, L. J.: Inverse problem in hydrogeology, *Hydrogeol J*, 13, 206–222, doi:10.1007/s10040-004-0404-7, 2005.
- Dagan, G.: *Statistical Theory of Groundwater Flow and Transport: Pore to Laboratory, Laboratory to Formation, and Formation to Regional Scale.*, *Water Resour. Res.*, 22, 120–134, doi: 10.1029/WR022i09Sp0120S, 1986.
- de Lange, W. and Borren, W.: *Grondwatermodel AZURE versie 1.0*, Tech. rep., Deltares, The Netherlands, 2014.
- Fiori, A., Dagan, G., and Jankovic, I.: Upscaling of Steady Flow in Three-Dimensional Highly Heterogeneous Formations, *Multiscale Model. Simul.*, 9, 1162–1180, doi:10.1137/110820294, 2011.
- Hendricks Franssen, H., Alcolea, A., Riva, M., Bakr, M., van der Wiel, N., Stauffer, F., and Guadagnini, A.: A comparison of seven methods for the inverse modelling of groundwater flow. Application to the characterisation of well catchments, *Adv. Water Resour.*, 32, 851 – 872, doi: 10.1016/j.advwatres.2009.02.011, 2009.
- Hoteit, I., Luo, X., and Pham, D.-T.: Particle kalman filtering: A nonlinear bayesian framework for ensemble kalman filters, *Mon. Weather Rev.*, 140, 528–542, doi:10.1175/2011MWR3640.1, 2012.
- Nilsson, B., Højberg, A. L., Refsgaard, J. C., and Trolborg, L.: Uncertainty in geological and hydrogeological data, *Hydrol. Earth Syst. Sci.*, 11, 1551–1561, doi:10.5194/hess-11-1551-2007, 2007.
- Nøtinger, B., Artus, V., and Zargar, G.: The future of stochastic and upscaling methods in hydrogeology, *Hydrogeol J*, 13, 184–201, doi:10.1007/s10040-004-0427-0, 2005.
- Rogiers, B., Vienken, T., Gedeon, M., Batelaan, O., Mallants, D., Huysmans, M., and Dassargues, A.: Multi-scale aquifer characterization and groundwater flow model parameterization using direct push technologies, *Environ Earth Sci*, 72, 1303–1324, doi:10.1007/s12665-014-3416-1, 2014.
- Sanchez-Vila, X., Guadagnini, A., and Carrera, J.: Representative hydraulic conductivities in saturated groundwater flow, *Rev. Geophys.*, 44, 1–46, doi:10.1029/2005RG000169, 2006.
- Valstar, J. R., McLaughlin, D. B., te Stroet, C. B. M., and van Geer, F. C.: A representer-based

inverse method for groundwater flow and transport applications, *Water Resour. Res.*, 40, W05 116, doi:10.1029/2003WR002922, 2004.

Vernes, R., van Doorn, T., Bierkens, M., van Gessel, S., and de Heer, E.: Van Gidslaag naar Hydrogeologisch Eenheid, Toelichting op de totstandkoming van de dataset REGIS II (in Dutch), Tech. rep., Nederlands Instituut voor Toegepaste Geowetenschappen TNO - Geological Survey of the Netherlands, Utrecht, the Netherlands, URL http://www2.dinoloket.nl/data/download/maps/resources/Rapport_NITG_05-038-B0115.netvers 2005.

Vernes, R. W. and van Doorn, T.: REGIS II, A 3D hydrogeological model of The Netherlands, in: Geological Society of America, Abstracts with Programs, vol. 38, p. 109, The Geological Society of America, Philadelphia, PA, USA, proceedings of the Philadelphia annual meeting of The Geological Society of America, 2006.

Zimmerman, D. A., de Marsily, G., Gotway, C. A., Marietta, M. G., Axness, C. L., Beauheim, R. L., Bras, R. L., Carrera, J., Dagan, G., Davies, P. B., Gallegos, D. P., Galli, A., Gómez-Hernández, J., Grindrod, P., Gutjahr, A. L., Kitanidis, P. K., Lavenue, A. M., McLaughlin, D., Neuman, S. P., RamaRao, B. S., Ravenne, C., and Rubin, Y.: A comparison of seven geostatistically based inverse approaches to estimate transmissivities for modeling advective transport by groundwater flow, *Water Resour. Res.*, 34, 1373–1413, doi:10.1029/98WR00003, 1998.