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Hydrology and Earth System Sciences
Discussions

Interactive comment on "The usefulness of outcrop analogue air permeameter measurements for analysing aquifer heterogeneity: testing outcrop hydrogeological parameters with independent borehole data" *by* B. Rogiers et al.

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The authors thank the referee for the constructive comments, which are addressed below:

The issues highlighted by referee #1 concern the description of the "Materials and Methods" section, the influence of larger cracks/pores on the estimated hydraulic conductivity, and the geostatistical analysis. We agree that the "Materials and Methods" section has to be extended to improve the clarity of the manuscript. We will include

more details on the air permeameter measurements, the conversion to saturated K, and the upscaling procedure in the revised version of the manuscript. We propose to change line 3-7, page 9694 to:

"Rogiers et al. (2013a) proposed a methodology to measure small-scale K variability from unconsolidated outcrop sediments and to calculate outcrop-scale equivalent K values. This methodology relies on air permeability measurements that are converted to saturated K values using the empirical equation from Iversen et al. (2003), and a subsequent numerical upscaling step. The air permeability measurements are performed with a hand-held air permeameter, the Tinyperm II (New England Research & Vindum Engineering, 2011), on a regular grid of measurement locations at the outcrop face. The TinyPerm II device has an inner tip diameter of 9 mm, resulting in an investigation depth of 9-18 mm, corresponding to a maximum spatial support of ~24 cm^3. Pressing the device plunger will create a vacuum to withdraw air from the outcrop sediments. A microprocessor analyzes the pressure increase, and returns air permeability. The resulting values cannot be converted directly to saturated hydraulic conductivity because corrections are needed in regards to i) the polar characteristics of water, ii) the fact that air at atmospheric pressure does not act as a true fluid continuum in soil (e.g. gas slippage might occur at the interface with solids), and iii) the difficulty in obtaining totally dry conditions in the investigated sediments. The use of empirical relationships like the one of Iversen et al. (2003) has proven to be very effective in converting air permeability into hydraulic conductivity."

We also agree with referee #1 that a clear overview table is necessary to improve the manuscript. We will insert a table (see Table 1 below) with the number, type, spacing and measurement support of the different data, for each lithostratigraphical unit. A separate paragraph will be added as well at the start of the "Materials and Methods" section, presenting this overview table:

"Table 1 provides an overview of all data used in this paper. The hydrogeological setting and the outcrop measurements are discussed first. The data at each outcrop has been upscaled to an equivalent K tensor. Next, the constant head measurements on the borehole core samples are discussed. The procedure for obtaining grain size distributions is described, and we shortly introduce the used pumping test methods and analyses. Finally we outline the approach for variography of the data to quantify spatial variability."

Table 1. Overview of the different K and grain size samples used in this paper. (See attached Fig. 1)

In the revised version of the manuscript, we will explain the origin of the empirical equation of Iversen et al. (2003), as proposed above. The numerical upscaling we refer to in line 6-7, page 9694, is the same as the one mentioned in lines 24-25, page 9694. This numerical upscaling approach will be outlined clearly as well in the revised version of the manuscript, by replacing line 23-26, page 9694 by:

"In addition to the individual air permeameter measurements (spatial support of $\sim$24 cm^3) and their statistics, the measurement grids were numerically upscaled to obtain equivalent horizontal and vertical K values at the scale of the outcrop (i.e., typically several m2; Rogiers et al., 2013a). This was done by using the approach of Li et al. (2011). The measurements on the sampling grid were converted into a numerical grid, with one extra grid cell at all sides. By invoking flow conservation for a combination of different boundary conditions an equivalent K tensor was obtained. An overview of this approach for all outcrops characterized by air permeameter measurements within the study area is provided by Rogiers et al. (2013b)."

During the measurements very few macropores were identified as K measurements were carried out beneath the root zone/biologically active zone. Concerning the REV, we measure at the cm-scale ($\sim$24 cm3) with the air permeameter, and use exactly 100 cm^3 for the borehole core samples. Rogiers et al. (2013a) demonstrated that the air permeameter measurements and 100 cm^3 core samples are compatible, and the small discrepancy in spatial support only is of minor importance. All campaigns with

this device (Beerten et al. 2012; Rogiers et al. 2013a,b; Huysmans et al. 2008; Possemiers et al. 2012) have indicated that the measurements are readily repeatable, and macropores created by surface processes were always avoided, if present at all. The measurement error is also small compared to the variability of the most homogeneous outcrop in this study. We will indicate the repeatability of the air permeameter measurements with this device in the revised version of the manuscript, and will provide the measurement error in terms of log10(K) variance, which can be compared directly to the variograms, by replacing line 26, page 9694 to line 3, page 9695 by:

"The individual small-scale air permeameter results show a correlation of 0.93 with independent constant-head laboratory permeameter measurements on 100 cm3 ring samples taken from the same outcrop measurement grid (Rogiers et al. 2013a). The average ratio between both log-transformed K data (air permeameter/constant head) equals 1.03, and is between 0.78 and 1.24 for individual samples. Repeatability of the TinyPerm II measurements was tested on a set of different lithologies with K ranging from 10-3.5 to 10-6.5 m/s, with maximum log10(K) error variance of 0.007. Given this high repeatability, and the absence of visible macropores in the investigated outcrop faces, the K data obtained from the outcrops is deemed accurate and unbiased."

We disagree with referee #1 that different REVs for the sandy and clayey sediments would partly explain higher similarity between outcrops and borehole cores for the sandy than for the clayey sediments. As indicated above, measurements of the air permeameter and on the borehole core samples are comparable in magnitude. For fractured or fissured clay lenses, whether in the outcrop or the aquifer sediments, there might reasonably be an REV-related problem. However, the clay lenses retrieved from the aquifer sediments do not show such fracturation or fissuration. The outcrop clay lenses on the other hand were sometimes heavily affected by weathering; by carefully selecting physically undisturbed parts of the clay air permeameter measurements were made that were not affected by preferential flow.

We understand the confusion due to the logarithmic axes of the variogram plots. This was done to visualize the outcrop data in similar detail as the borehole data, which is gathered at larger distances. The use of linear axes does however provide similar conclusions. Therefore we propose to change the axes of the plots to linear in the revised version of the manuscript (see Figure 8 below), which is a more conventional way of displaying variograms. As suggested by the reviewer, we will insert the root mean squared error of the fitted variogram models in Table 1 (Table 2 in the revised manuscript; see below), and discuss the fits accordingly in section "3.6 Spatial variability":

"For the Mol formation, the variogram model root mean squared errors (RMSE; Table 2) show that fitting both datasets simultaneously improves the fit, mainly due to the very low outcrop semivariances that are compatible with the borehole data. For the sandy part of the Kasterlee Formation, the datasets are not compatible and the joint pure nugget fit shows the highest RMSE. For the clayey Kasterlee Formation, both datasets seem to be compatible, except for the borehole data point with the smallest lag distance. For the clayey Diest Formation, the variogram models are very similar, as are the RMSE values. For the sandy Diest Formation, the range is very different, but the sill values are similar."

Table 2. Overview of fitted spherical variogram model parameters for the vertical experimental variograms (range = correlation length). The outcrop data is taken from Rogiers et al. (2013a). The root mean squared error (RMSE) is provided as a measure of goodness of fit. (See attached Fig. 2)

Fig. 8. Comparison between vertical experimental and modelled semivariograms (fitted using a least squares approach) for outcrop and borehole data. (A) Mol Fm, (B) sandy Kasterlee Fm, (C) clayey Kasterlee Fm, (D) clayey Diest Fm, and (E) sandy Diest Fm. The fit diagnostics are provided in Table 1. (See attached Fig. 3)

As explained in the "Variography" section, we use the minimum semivariance, data variance and maximum lag distance as initial values for the nugget, total sill and variogram ranges.

In case of singular model fits, the responsible parameters were fixed at their initial value, before re-initialising the model fitting. This indeed may lead to certain sill and range values, where the experimental variogram could be fitted by a linear model as well. However, given the lack of larger lag distances, we choose to keep these initial values data-based. In the revised version of the manuscript, we will insert before line 25, page 9705:

"The sill and range for the variograms that have not reached a constant semivariance within a lag distance of 14 m (Figure 8A, E), are highly uncertain as a linear model would provide an equally poor description of the data as the used spherical model. The semivariance within the distance range of the experimental data (up to 10-15 m), is however hardly affected by this."

References not cited in the current version of the manuscript:

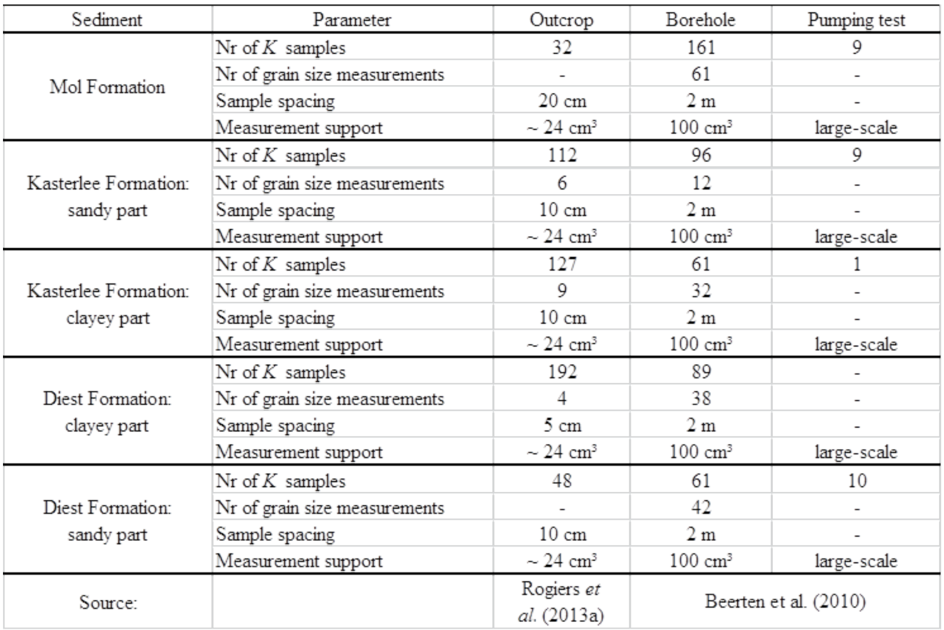
Huysmans M, Peeters L, Moermans G, Dassargues A. 2008. Relating small-scale sedimentary structures and permeability in a cross-bedded aquifer. Journal of Hydrology 361(1-2): 41-51.

Li L, Zhou H, Gómez-Hernández JJ. 2011. A Comparative Study of Three-Dimensional Hydraulic Conductivity Upscaling at the MAcro-Dispersion Experiment (MADE) site, Columbus Air Force Base, Mississippi (USA). Journal of Hydrology 404(3-4): 278-293.

New England Research & Vindum Engineering. 2011. TinyPerm II Portable Air Permeameter, UserÊijs Manual. Retrieved from http://www.vindum.com/TinyPermManual.pdf on 14-06-2011.

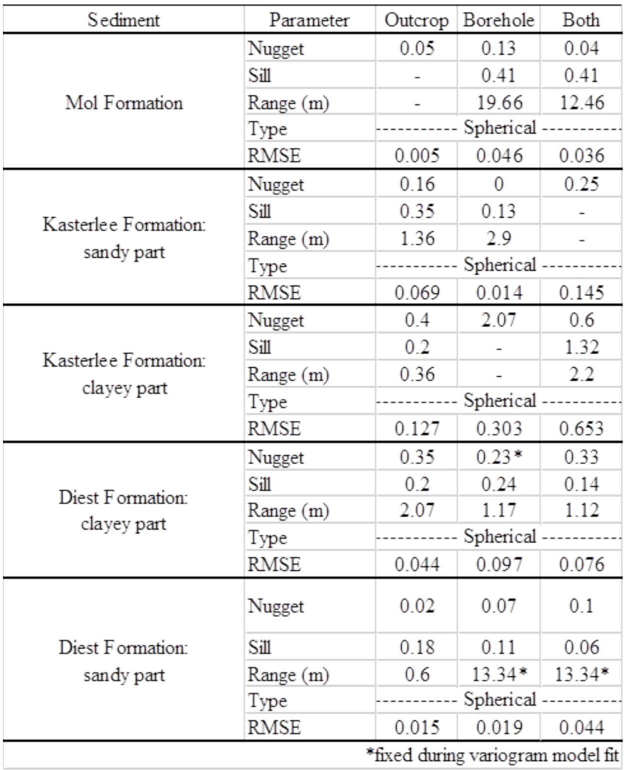
Possemiers M, Huysmans M, Peeters L, Batelaan O, Dassargues A. 2012. Relationship between sedimentary features and permeability at different scales in the Brussels Sands. Geologica Belgica 15(3): 156-164.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 10, 9689, 2013.



Sediment	Parameter	Outcrop	Borehole	Pumping test
Mol Formation	Nr of K samples	32	161	9
	Nr of grain size measurements	-	61	-
	Sample spacing	20 cm	2 m	-
	Measurement support	~ 24 cm³	100 cm³	large-scale
Kasterlee Formation: sandy part	Nr of K samples	112	96	9
	Nr of grain size measurements	6	12	-
	Sample spacing	10 cm	2 m	-
	Measurement support	~ 24 cm³	100 cm³	large-scale
Kasterlee Formation: clayey part	Nr of K samples	127	61	1
	Nr of grain size measurements	9	32	-
	Sample spacing	10 cm	2 m	-
	Measurement support	~ 24 cm³	100 cm³	large-scale
Diest Formation: clayey part	Nr of K samples	192	89	-
	Nr of grain size measurements	4	38	-
	Sample spacing	5 cm	2 m	-
	Measurement support	~ 24 cm³	100 cm³	large-scale
Diest Formation: sandy part	Nr of K samples	48	61	10
	Nr of grain size measurements	-	42	-
	Sample spacing	10 cm	2 m	-
	Measurement support	~ 24 cm³	100 cm³	large-scale
Source:		Rogiers *et al.* (2013a)	Beerten et al. (2010)	

Fig. 1. Overview of the different K and grain size samples used in this paper.



Sediment	Parameter	Outcrop	Borehole	Both
Mol Formation	Nugget	0.05	0.13	0.04
	Sill	-	0.41	0.41
	Range (m)	-	19.66	12.46
	Type	----------	Spherical	----------
	RMSE	0.005	0.046	0.036
Kasterlee Formation: sandy part	Nugget	0.16	0	0.25
	Sill	0.35	0.13	-
	Range (m)	1.36	2.9	-
	Type	----------	Spherical	----------
	RMSE	0.069	0.014	0.145
Kasterlee Formation: clayey part	Nugget	0.4	2.07	0.6
	Sill	0.2	-	1.32
	Range (m)	0.36	-	2.2
	Type	----------	Spherical	----------
	RMSE	0.127	0.303	0.653
Diest Formation: clayey part	Nugget	0.35	0.23*	0.33
	Sill	0.2	0.24	0.14
	Range (m)	2.07	1.17	1.12
	Type	----------	Spherical	----------
	RMSE	0.044	0.097	0.076
Diest Formation: sandy part	Nugget	0.02	0.07	0.1
	Sill	0.18	0.11	0.06
	Range (m)	0.6	13.34*	13.34*
	Type	----------	Spherical	----------
	RMSE	0.015	0.019	0.044

*fixed during variogram model fit

Fig. 2. Overview of fitted spherical variogram model parameters for the vertical experimental variograms (range = correlation length). The outcrop data is taken from Rogiers et al. (2013a). The root mean ...

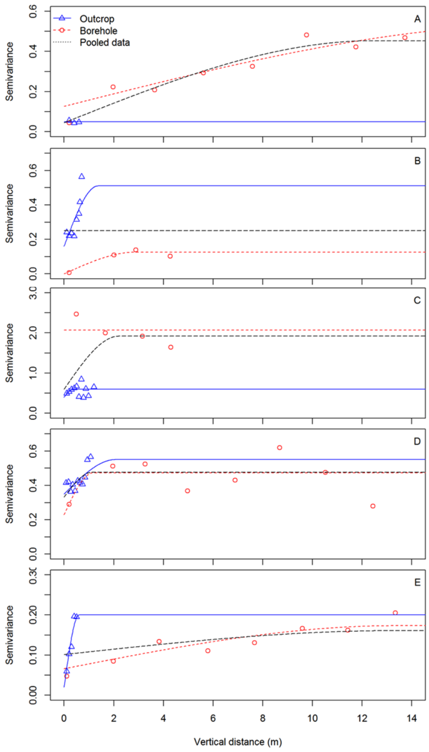


Fig. 3. Comparison between vertical experimental and modelled semivariograms (fitted using a least squares approach) for outcrop and borehole data. (A) Mol Fm, (B) sandy Kasterlee Fm, (C) clayey Kasterlee ...