Final response

Referee comment on "Calibration of groundwater seepage on the spatial distribution of the stream network to assess catchment-scale hydraulic conductivity" by Ronan Abhervé et al., Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2022-175-RC1, 2022

Referee comments are shown in black*. Our responses in blue italic.*

RC1: 'Comment on hess-2022-175', Anonymous Referee #1, 09 Oct 2022

General comment:

In the submitted manuscript, Abhervé et al present a study that deals with the estimation of hydraulic conductivity at the catchments scale. Solving the groundwater flow equation for R/K (R: long term recharge, K: catchment-scale hydraulic conductivity), the authors try to find most realistic values of K for 24 catchments in north-western France with different geologies, for which they compare simulated stream network extent with independently derived stream network maps. As a measure of similarity, they use the difference of the averaged over- and under-estimated stream network lengths. The results show that estimated K values cluster by the geologies of the 24 catchments with increasing estimated Ks towards more permeable rock types (Limestone). Sensitivity analysis shows that the resolution of the available DEM for estimating K is much less important than the stream map product to calculate most suitable K estimate.

Overall, the topic of the study and the produced results are of great value for the hydrological community and beyond since K estimates are usually available on much smaller scales (points to contributing areas of wells during pumping tests). The presented approach would provide K estimates at a scale most useful to be transferred into prediction models.

Answer:
We are thankful to the reviewer for highlighting the interest of the developed methodology and its value for the hydrological community. All comments and suggestions raised by the reviewer are considered in the new version of the manuscript.

However, I see two major weaknesses that need to be addressed until this work can be considered for publication:

- There is a lack of reference to proceeding studies and methods to estimate K both in the introduction and the (very short) discussion. Although the authors estimate K at the catchments scale, they should provide more information about existing approaches to estimate K (e.g. well cores, pumping tests, model calibration) and for which scale they are applicable. There should also be more information on previous work trying to up-scale this information for large-scale modelling. Hartmann and Moosdorf are mentioned but no information about their upscaling approach and the range of K values they obtained. Also, there is some recent work on earth-tides and their usability for K estimation on larger scales. There is also need for mentioning typical ranges of K for different lithologies found by different studies or provided by established textbooks (e.g., Freeze & Cherry).

Answer:
We agree with this comment. We will provide a more exhaustive review of existing methods in the introduction, as follow:

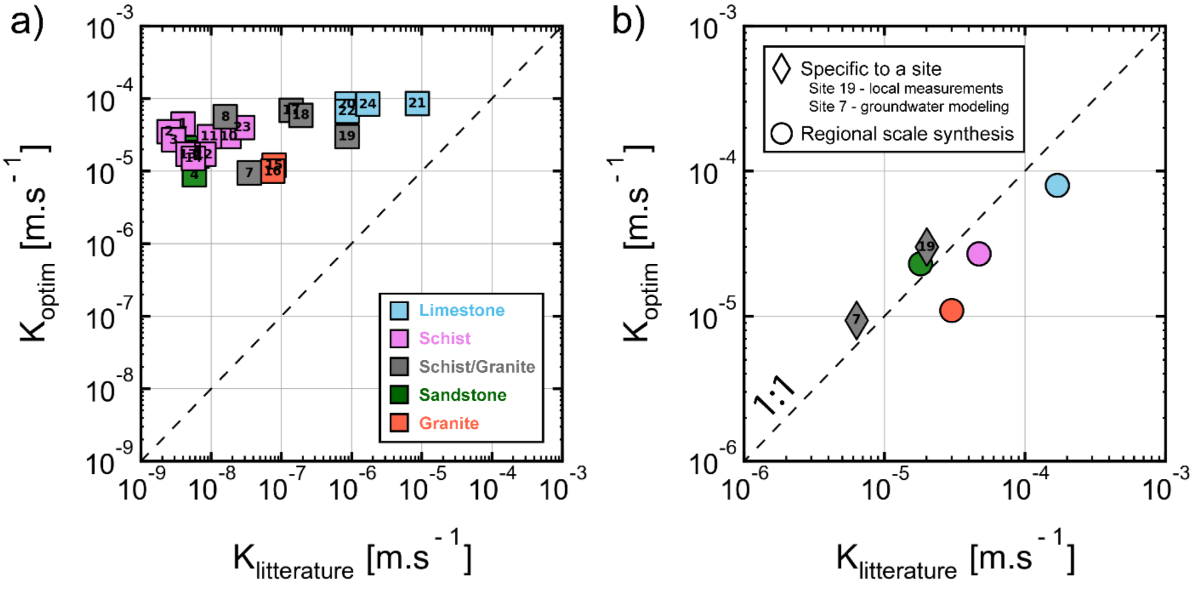
> *"Hydraulic conductivities are classically estimated using hydraulic tests involving centimeter scales for laboratory experiments up to decameter scales for well tests (Freeze & Cherry, 1979). Analysis of streamflows (Brutsaert & Nieber, 1977; Mendoza et al., 2003; Troch et al., 2013; Vannier et al., 2014), earth tides (Hsieh et al., 1987; Rotzoll & El-Kadi, 2008) and borehole head dynamics (Clauser, 1992; Renard, 2005) provide alternative ways to estimate effective hydraulic properties at larger and to calibrate hydrological models (Chow et al., 2016; Eckhardt & Ulbrich, 2003; Etter et al., 2020). Multiparameter calibration has been proposed to reduce uncertainties, by considering additional data like temperature (Bravo et al., 2002), groundwater ages derived from environmental tracers (Kolbe et al., 2016) or continuous geochemical monitoring (Schilling et al., 2019). Recent advances in machine learning technics show promising results to propose new relations between permeability and streamflows and more generally between models and data (Cromwell et al., 2021; Marçais & de Dreuzy, 2017; Reichstein et al., 2019). Converging to the challenging issues of upscaling (Clauser, 1992; Hsieh, 1998) and characterizing ungauged catchments (Beven et al., 2020; Blöschl et al., 2019), these methods are completed by the constitution of global databases compiling hydraulic conductivities (Achtziger-Zupančič et al., 2017; Comunian & Renard, 2009; Kuang & Jiao, 2014; Ranjram et al., 2015). By compiling regional-scale permeabilities from groundwater models calibrated according the lithologies, (Gleeson et al., 2011, 2014) proposed a global-scale hydraulic conductivity map, updated in GLHYMPS 2.0 (Huscroft et al., 2018), based on a high-resolution global lithology map (GLiM) (Hartmann & Moosdorf, 2012) raising concerns on local relevance (de Graaf et al., 2020; Reinecke et al., 2019; Tashie et al., 2021)."*

We will also complete the discussion to put our results in perspective with previous estimates of catchment-scale hydraulic properties. We provide more details on the new discussion outline at the end of this review report.

- There is a lack comparison to K values obtained by different approaches and studies. The authors relate their results to the works of Stoll and Weiler (2010) and Lou et al. (2010), who used very similar methods. But I would expect more comparison and discussion to independently derived K values, ideally for some of the test sites but at least to typical ranges provided in textbooks (e.g. Freeze & Cherry) or the values provided from up-scaled map like the one of Hartmann and Moosdorf (note that there are more recent versions of the global permeability map available). Generally, the values found here seem to be quite similar compared to the differences of several orders of magnitude for different geologies mentioned in Freeze & Cherry or even in Stoll and Weiler (2010).

Answer:

We suggest to add a dedicated section along with figures that will allow comparison of our results to K values obtained by different approaches. Specifically, we will provide the readers a comparison of our estimates with the ones compiled in the well-known GLHYMPS 2.0 database (Huscroft et al., 2018) (Figure RC1 1a). In addition, we will compare our K results with the ones obtained by independent local approaches using hydraulic tests (Le Borgne et al., 2006) (BRGM, 2018) and numerical groundwater flow model (Kolbe et al., 2016).



Global database (GLHYMPS) Local hydraulic tests

Figure RC1 1. a) Optimal hydraulic conductivities estimated by the proposed calibration method for each of the 24 catchments studied, compared a) with the average K values provided by the GLHYMPS 2.0 global permeability database (Huscroft et al., 2018) and b) with regional synthesis of values from hydraulic tests (BRGM, 2018), local hydraulic tests for site 19 (Le Borgne et al., 2006) and groundwater modelling calibration for site 7 (Kolbe et al., 2016). Values provided in transmissivity by the literature are translated into hydraulic conductivity assuming the same constant aquifer thickness as the one used in this study (30 m).

Noteworthy, while GLHYMPS 2.0 data shows one to several orders of magnitudes lower (Figure RC1 1a), local values are much closer within -33 % to 172 % indicating possible bias and scale effects. We will detail this important point in the new version of the discussion.

For those reasons, and for the more specific comments in the following, I recommend major revisions.

Specific comments:

- The introduction provides the motivation of the study and moves quickly to methodological aspects (LL 46 and following). Please move methodological parts to the methods section and provide a more detailed review of the state of the art of K estimation identifying the research gap addressed by this study.

Answer:
The state of art of K estimation will be updated as previously shown. The methodological aspects will be moved to the methods section in the new version of the manuscript.

- Equation (1) describes anisotropic conditions (different Ks in the directions of x, y and z), while K estimates of this study assume isotropic conditions (no specification of K direction). Please simplify Eq (1) or clarify why the more complex version of the equation is shown here. Also, shouldn't W have the unit [L T-1] and not [T-1] as indicated in L 114?

Answer:
In fact, we modify the equations and units to the following simpler versions:

$$\nabla . (hK\nabla h) = q \qquad (1)$$

where h [L] is the hydraulic head, K [L T^{-1}] is the hydraulic conductivity, q [T^{-1}] is the volumetric flux per unit volume.

- I am not sure if the performance metric J, as specified in Eq (2) will give you the best estimation of K of a given catchment. Since real geological systems are always heterogeneous and anisotropic, a best estimate of a catchment's K might give you a small over-estimation and a larger under-estimation of stream lengths, while J would find its optimum when both lengths are the same. Why did you not choose a metric that minimizes both over- and underestimation?

Answer:
The proposed performance metric allows for a compromise between over- and under-estimation. It does not necessarily lead to the minimum deviation, but it ensures a minimum bias, though both methods would lead to close values of K. We will add a note in the manuscript to highlight this point.

The point concerning heterogeneity and anisotropy is important. The methods could be extended to analyse the lateral heterogeneity by applying it independently on the different lithologies. For example, in Figure 6 of the manuscript, we identify the effect of this lateral heterogeneity for site 8. On this site, we found that in the northern part of the catchment our simulation results fail in modelling the observed stream network on the granite lithology, while it overestimates its extent on the schist/sandstone lithology. This suggests that the obtained bulk hydraulic conductivity is slightly overestimated for the granite-dominated part of the catchment while being underestimated for the schist part. This point will be further discussed in the future version of the manuscript (refer to the last question/answer).

- Subsection 3.1 provide new methods Eqs (3-5), which should be moved to the methods section.

Answer:
The equations and description will be moved to the method section.

- The Discussion section is much too short and it should be separated from the conclusions. Please discuss here your assumptions and resulting uncertainty, compare to more other studies (not just Stoll & Weiler and Lou et al.), and explain under which conditions and how the approach can be applied at other catchments and the limits of transferability.

Answer:
We agree with the reviewer. In the new version, the conclusion section will be devoted to the perspectives and will be separated from the discussion. The discussion will be further completed by considering the different points mentioned by the reviewer. In the following we propose a new outline of the discussion based on the ensemble of comments:

Discussion outline

- Overview of the proposed methodology and its efficiency to predict the extent of the observed stream network

- Comparison with methods that also rely on the hydrographic network:
    · indicator to identify permeable or impermeable areas (Mardhel et al., 2021)
    · performance criteria to compare stream networks (Franks et al., 1998; Güntner et al., 2004)
    · estimation of K using an observed stream network (Luo et al., 2010; Stoll & Weiler, 2010)

- Comparison of our K estimates with other approaches, including:
    · global hydraulic conductivity map (Huscroft et al., 2018)
    · regional well tests compilation (BRGM, 2018)
    · numerical model (Kolbe et al., 2016)
    · textbooks (Freeze & Cherry, 1979)

- Sensitivity of the method, assumptions, and resulting uncertainties. We will specifically discuss:
  - *the impact of the aquifer thickness on the estimation of transmissivity and K*
  - *the sensitivity of the resolution of the DEM and the observed stream network*
  - *the limitations of considering homogeneous hydraulic properties and recharge*

- Opportunities to deploy the method in other contexts
  - *hydrogeological contexts in which the method is applicable*
  - *further improvements to be made to allow its deployment in other geomorphic and hydrological contexts.*

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