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Interactive comment on "Interpretation of Multi-scale Permeability Data through an Information Theory Perspective" *by* Aronne Dell'Oca et al.

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Interactive comment by anonymous reviewer on "Interpretation of Multi-scale Permeability Data through an Information Theory Perspective" by Aronne Dell'Oca, Monica Riva and Alberto Guadagnini (https://doi.org/10.5194/hess-2019-628).

Dear Editor:

We appreciate the efforts that you and the anonymous Reviewer have invested in our manuscript. We here detail the actions we envision to address the Reviewer's comments and inputs. Please, find below an item by item list where our envisioned actions

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are indicated in plain font, to distinguish them from the Reviewer's comments (in italic). Our revised manuscript will be uploaded following closure of the discussions phase.

Summary and Recommendation

The authors use well-known information-theoretic quantities to quantify information content and information transfer among permeability datasets collected at different scales. The explanation of the quantities is thorough, but it is not clear to which extent the presented results are affected by the choice of the settings for the methodology (binning, bandwidth, ...) or how the information extracted from the datasets can be used in practice. I advise the authors to carefully review the manuscript, expanding the investigation to the analysis of the impact of "setting parameters" and presenting some ideas on the practicality of the analysis.

We thank the Reviewer for his/her efforts and time. We will provide additional details on the impact of the number of bins and the size of the bandwidth of the kernel (i) in the manuscript and (ii) as supplementary material (in details). We will add a discussion section in the revised manuscript where we clarify the potential use and transferability of the current analysis in the context of practical applications.

Specific comments

Please investigate the role of binning with respect to the presented results - how do you choose the bandwidth? Does it have an influence on the results?

We thank the Reviewer for pointing this out. We will provide additional details on the assessment of the impact of the number of bins and of the size of the kernel bandwidth on the presented results. Our revised text now reads: "We inspect how the IT metrics described in Section 2 vary as a function of (i) the number of bins (i.e., we consider a number of 50, 75, 100, and 125 bins for the discretization of the range of data variability) and (ii) the size of the kernel bandwidth (which is varied within the range 0.1 - 0.4) employed in the KDE routine (see Supplementary Material SM1-3 for additional

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details). This analysis highlights a weak dependence of the values of the investigate IT metrics on the number of bins and on the size of the bandwidth employed in the Kernel Density Estimator (KDE) procedure. However, the overall patterns of these metrics remain substantially unaffected. This leads us to use 100 bins and a kernel bandwidth equal to 0.3. Note that we consistently employ this binning for the evaluation of all metrics introduced in Section 2.”. We will also include all details about these issues as supplementary material.

Does the fact that permeability is by its nature a process-dependent (or model-dependent) quantity affect the applicability of the procedure?

We do not see why the nature of permeability, including its scale dependence as an effective parameter associated with the flow equation, should hamper the applicability of the procedure. This is also in line with the consolidated use of standard geostatistical approaches for the stochastic characterization of heterogeneity of aquifer systems.

Could you please discuss: - how often multi-scale permeability measurements are available - how the presented results are transferable - how the presented results can be used in practical applications

We thank the Reviewer his/her comment. We will address these aspects by adding relevant references. Our revised text now reads (Section 5): “Considering an operational context, including, e.g., groundwater resource management or (conventional/unconventional) oil recovery, we observe that it is common to have at our disposal permeability data associated with diverse support scales. These can be inferred from, e.g., large scale pumping tests, downhole impeller flowmeter measurements, core flood experiments at the laboratory scale, geophysical investigations, or particle-size curves (see e.g., Paillet, 1989; Day-Lewis et al., 2000; Zhang and Winter, 2000; Pavelic et al., 2006; Neuman et al., 2008; Riva et al., 2099; Barahona-Palomo et al., 2011; Quinn et al., 2012; Shapiro et al., 2015; Galvão et al., 2016; Menafoglio et al., 2016; Medici et al., 2017; Dausse et al., 2019, and reference therein). Assessing (i) the information content and (ii) the amount of information shared between permeability data associated with differing support scales (and/or diverse measuring devices/techniques) along the lines illustrated in the present study can be beneficial to obtain a quantitative appraisal of possible feedbacks among diverse approaches employed for aquifer/reservoir characterization. Results of such an analysis can potentially serve as a guidance for the screening of datasets which are most informative to provide a comprehensive description of the spatially heterogeneous distribution of permeability. While the methodology detailed in Section 3 is readily transferable to scenarios where multi-scale permeability are available, the appraisal of the general nature of some specific findings of the present study (e.g., decrease of the Shannon entropy as the support scale increases, regularity in the trends displayed by the normalized bivariate mutual information) still remains an open issue."

Lines 85-86: please expand the literature review to include several works on the use of information-theory quantities for porous material characterization.

We thank the Reviewer his/her comment. Our revised text now reads (Section 1): "To the best of our knowledge, as compared to surface hydrology systems only a limited set of works consider relying on IT concepts to analyze scenarios related to processes taking place in subsurface porous media. Nevertheless, we note a great variety in the topics covered in these works, reflecting the broad applicability of IT concepts. These studies include, e.g., the works of Woodbury and Ulrych (1993, 1996, 2000) who apply the principle of minimum relative entropy to tackle uncertainty propagation and inverse modeling in a groundwater system. The principle of maximum entropy is employed by Gotovac et al. (2010) to characterize the probability distribution function of travel time of a solute migrating within a heterogeneous porous formation. Within the same context, Kitanidis (1994) leverage on the definition of entropy and introduced the concept of dilution index to quantify the dilution state of a solute cloud migrating within an aquifer. Mishra et al. (2009) and Zeng et al. (2012) evaluate the mutual information shared between pairs of (uncertain) model input(s) and output(s) of interest, and

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view this metric as a measure of global sensitivity. Nowak and Guthke (2016) focus on sorption of metals onto soil and the identification of an optimal experimental design procedure in the presence of multiple models to describe sorption. Boso and Tartakovsky (2018) illustrate an IT approach to upscale/downscale equations of flow in synthetic settings mimicking heterogeneous porous media. Relaying on IT metrics, Butera et al. (2018) assess the relevance of non-linear effects for the characterization of the spatial dependence of flow and solute transport related observables. Bianchi and Pedretti (2017, 2018) developed novel concepts, mutuated by IT, for the characterization of heterogeneity within a porous system and its links to salient solute transport features. Wellman and Regenaur-Lieb (2012) and Wellman (2013) leverage on IT concepts to quantify uncertainty, and its reduction, about the spatial arrangement of geological units of a subsurface formation. Recently, Mälicke et al. (2019) combine geostatistic and IT to analyze soil moisture data (representative of a given measurement scale) to assess the persistence over time of the spatial organization the soil moisture, under diverse hydrological regimes".

Lines145-147: please clarify meaning and implications

We thank the Reviewer his/her comment. We have further clarified our choice. Our revised text now reads: "While corresponding definitions are available also for continuous variables (i.e., summation(s) and probability mass function(s) are replaced by integral(s) and probability density function(s), respectively), these are characterized by a less intuitive and immediate interpretation (e.g., Entropy could be negative, infinite or could not be evaluated in case of probability density function(s) involving a Dirac's delta since its logarithm is not defined; see e.g., Cover and Thomas, 2006; Kaiser and Schreiber, 2002). Moreover, in case no analytical expressions are available for the demanded probability density functions of the analyzed continuous variables, a quantization of the latter is necessary in order to estimate the IT metrics associated with the continuous variables through their quantized counterparts (see Cover and Thomas, 2006). In general, the quality of these estimates increases (in different manners depending on the specific metric) with the level of quantization of the continuous variables (see e.g., Kaiser and Schreiber, 2002)."

Technical comments A few typos: line 284, line 254. We thank the Reviewer his/her comment. We will duly correct the typos in the revised manuscript.

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Please also note the supplement to this comment:
https://www.hydrol-earth-syst-sci-discuss.net/hess-2019-628/hess-2019-628-AC2-supplement.pdf

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