

Reply on RC1

Chloé Fandel et al.

Author comment on "Improving understanding of groundwater flow in an alpine karst system by reconstructing its geologic history using conduit network model ensembles" by Chloé Fandel et al., Hydrol. Earth Syst. Sci. Discuss., <https://doi.org/10.5194/hess-2022-280-AC1>, 2022

We appreciate the insightful and constructive comments from Reviewer 1, and we agree that addressing them will result in stronger work overall. In the following paragraphs, we provide specific responses and also explain the planned modifications in the revised paper:

Comment: In the document the authors state that the simulation of the networks for a resolution of 50x50 meters can be performed in less than 2 minutes. In this sense, what is the limiting factor for not using a map with a higher resolution?

Response: The basic reason for not including a higher resolution is that a high resolution is not needed to answer the question that is treated in this paper. We compared the results of a higher-resolution model with 5x5 meter cells to the result of the lower-resolution model with 50x50 meter cells. The higher resolution significantly increased the computation time (nearly 50 minutes compared to less than 2 minutes), and produced conduit networks that followed the same general paths and orientations as those in the low-resolution model. Because the goal of this paper is to reconstruct the regional-scale geologic events controlling past conduit evolution, and not to generate detailed cave maps, we chose to use the more rapid lower-resolution model, which provided enough information for our purposes. Higher-resolution 3D models would bring additional information if more detailed input data were considered, but this is not relevant to our primary question.

Comment: In Figure 3, how is the expected network defined?

Response: The expected network was originally defined by Chen and Goldscheider (2014), and refined by Chen et al. (2018), based on geologic mapping by Wagner (1950), predominant fracture orientations documented by Cramer (1959), several decades of speleological investigations by the regional caving club (Höhlenverein Sonthofen), 18 quantitative multi-tracer tests by Goldscheider (2005), Göppert and Goldscheider (2008), and Sinreich et al. (2002), and hydrogeological field observations by Goldscheider (2005). There is a sentence to this effect around line 80, but we will edit it to make it more clear that this refers to the expected conduit network.

Comment: In Figure 3, is it possible to draw the expected network with different plotting settings to enhance its visibility? As it is, the expected network can be confused with the simulated conduits.

Response: Yes, thank you for pointing this out. We will make the expected network a different color from the simulated networks.

Comment: Could you provide an interpretation of the variability of the simulated conduits? Is it an indicator of the uncertainty of the expected conduit? Could you include a metric to measure such variability?

Responses:

Question 1: The variability in the simulated conduits is a result of the model's stochastic nature. Stochasticity can be introduced in several ways, but for this study, in the simulations of the competing scenarios under consideration, the primary source of stochasticity is the fracture network. For each conduit simulation, a new fracture network is generated, based on the descriptive statistics obtained from field and aerial photo mapping of the actual fracture network. The conduits then form preferentially along fractures, resulting in slightly different networks for each simulation. This is described around line 130, but the explanation will be further improved in the revised paper.

Question 2: In regions of the model strongly controlled by fractures, there will be more variability in the ensemble in response to the different fracture networks in each simulation. In regions of the model where other factors (such as gradient, existing conduits, or obstacles) are more dominant, there will be less variability in the ensemble. The "fuzziness" of the ensemble maps (more fuzzy = more variability in where different model simulations predict conduits will go) is an indicator of model uncertainty. Regions where the different model simulations all predict different conduit paths would be regions where we have low confidence in the model's predictive abilities, and where we would be interested in acquiring more data. Regions where the different model iterations cluster tightly around a single path would be regions where we have higher confidence that a conduit is indeed in the model-predicted location, and we would not prioritize collecting additional data. This is discussed in more depth in Fandel et al. (2021). We will add text with a brief overview of the source of variability, pointing readers to our previous work for a more in-depth explanation.

Question 3: This is an excellent question, and is one that we have been exploring at length, and do not yet have a satisfying answer to. Quantifying the similarity or dissimilarity of conduit networks is challenging. One approach is to represent the networks as mathematical objects: graphs with nodes connected by edges. Statistics can then be computed describing the geometry and topology of these graphs. Collon et al. (2017) describe the statistics most relevant to describing karst networks, and we have incorporated their functions to calculate these statistics into the pyKasso model code. However, these statistics quantify strong differences in the topology of the networks and are more relevant to classifying different types of cave networks, or to determining how closely modeled networks match mapped networks. When attempting to quantify the degree of variability in our simulated conduits, the models in our ensembles are statistically similar enough to each other that we cannot distinguish between them based on available geometrical and topological metrics. If, given these considerations, it would still be interesting to include this information, we could insert a table showing summary statistics for our ensembles. Identifying statistical metrics that can usefully describe differences between models of the same network in an ensemble is an area of future research that we are highly interested in pursuing further, but we consider that our results are not mature enough and that that topic is beyond the scope of this paper.

Comment: In line 243 the authors mention that there is an additional scenario that is not explored in this study. Is there any justification for not analyzing it?

Response: The scenario in question is that there were several overlapping phases of

karstification, in which different combinations of springs were either exposed or occluded. While the two scenarios we explored were supported by enough geologic, hydrogeologic, and geomorphologic observations to define clear hypotheses, this is not the case with the additional scenario. Furthermore, one of the two tested scenarios delivered cave patterns that match the observed cave pattern very well, suggesting that this is how the caves have essentially formed. For these reasons, we decided not to test the additional scenario in detail. We agree that the statement about the "additional scenario" in line 243 causes confusion and distracts from the logical sequence of our research work. Therefore, we will delete this statement and not mention any "additional scenarios" in the revised paper.

Comment: In line 125 the authors wrote that in this study you are considering that conduits form preferentially in the direction of the maximum downward hydraulic gradient. Could you please add some references to studies where this assumption is also employed? Alternatively, could you please add some words explaining the reasoning behind this assumption?

Response: The hydraulic gradient is the driving force of groundwater flow (i.e., groundwater always flows from high to low hydraulic potential), and flowing groundwater containing CO₂ is the key agent of cave formation (speleogenesis) in limestone. Fracture characteristics, lithological differences and several other aspects and processes also influence the formation and orientation of conduits, but the hydraulic gradient is the key driver in most cases. This is discussed in classical scientific literature about caves (e.g. Palmer 2007) but also in numerous studies dealing with the modeling of speleogenesis (papers by Dreybrodt, Gabrovsek and others). In shallow and mostly unsaturated settings, such as our example, hydraulic gradients largely coincide with topographic gradients; in deep and artesian settings, however, groundwater can flow upwards, but it always follows the hydraulic gradient, and the conduit network reflects this flow direction. In the revised paper, we will briefly explain and discuss this important aspect, supported by relevant additional references.

Comment: In Section 6 (Findings) you do some references to Figure 4. However, they seem to refer to elements in Figure 5.

Response: Thank you for catching this mistake! We will correct the figure references.

Comment: There is a missing closing bracket in line 112.

Response: Thank you for catching this. We will insert the missing bracket.