Representing uncertainty using diverse model ensembles: A test case in an alpine karst system

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Problem

Karst aquifers are difficult to model because flow through conduits, rather than pore spaces, leads to high structural uncertainty. Existing models rely either on detailed conduit maps, or on averaged parameters approximating a porous medium. Neither approach is adequate for most karst systems, where conduits are unmapped, yet flow patterns are fundamentally different from those in porous media.

We are testing a new approach to modeling karst based on generating a large model ensemble from minimal data, then adjusting the ensemble based on model performance. This adjusted ensemble can then be used to project future behavior under different conditions.

Study site

The Gottesacker-Schwarzwassertal karst system (German-Austrian Alps) is a long-term study site with complex hydrogeology (Fig. 1). The primary karstifiable unit in the 35 km² basin is the ~100 m-thick Schrattenkalk limestone, which is strongly folded and fractured. Karst conduits drain the system into three major outlets: an estavelle (QE), the Aubach spring (QA), and the Sagenbichl spring (QS). Over 25 years of pre-existing data are available for this site, including geologic maps, tracer test data, cave maps, and results from previous modeling efforts (which we use as our base model)3.

To generate the initial model ensemble, we set aside almost all the available data and used only the orientation of major fracture families. We recorded the choices made for a. Location of the Gottesacker-Schwarzwassertal karst system, in the German-Austrian Alps.

Next steps

The initial ensemble can be weighted to reflect the likelihood that each conduit network will simulate observed spring discharge behavior. We plan to weight the ensemble using a Monte Carlo Tree Search4, which balances exploring the model space with exploiting good-fit models. Each network in the initial ensemble is run once with randomly-assigned SWMM flow parameters, and ranked by likelihood of reproducing observed spring discharge. The probability of a conduit model being selected and run again with a new set of random parameters is based on its initial likelihood. After each new run, the likelihoods of the entire ensemble are updated. At the end of the tree search process, the ensemble can be used to generate likelihood-weighted predictions of system behavior.

Questions

• Are conceptual modeling decisions fundamentally different than parameter value choices?
• Is the Monte Carlo tree search method the most appropriate/efficient way to search model space?
• Currently, many models in the ensemble are not behavioral. What strategies could increase the percentage of behavioral models?
• Precipitation inputs are calculated from only a few rain gages, but the strong elevation gradient suggests that precipitation is highly spatially variable. How could precipitation be spatially distributed?

References


Acknowledgements

Thank you to the KIT dope: Applied Geomechanics for hosting me for a three year research stay, and to Prof. Wolfgang Nowak & his research group for suggesting the Monte Carlo Tree Search approach.

Figure 1: Site location

a. Location of the Gottesacker-Schwarzwassertal karst system, in the German-Austrian Alps. b. Schematic diagram of the hydrogeology of the system: karst groundwater flows along the synformal axes, which drain into a deeper zone where flowpaths can cut across the folds before emerging at springs.

Figure 2: Modeling process

a. One realization of a 3D geologic block model of the system, created in GemPy5. b. (i) One realization of a conduit network, generated by the Stochastic Karst Simulator4. (ii) Heatmap of fifty conduit network realizations (gray), compared to the network used in the base model of the site3 (blue). c. Fifty predictions of spring discharge behavior (one per conduit network) with randomly-assigned flow parameters, returned by the Storm Water Management Module5.

Figure 4: Model tree

Tree structure for the SKS portion of a mini model ensemble of only eight models. Each node represents a conceptual choice, with the last node on each branch corresponding to one conduit model in the ensemble. The ID string of each model records the series of choices that generated that particular model (labeled in the table). A randomly-chosen set of SWMM parameters are then assigned to each conduit model. The color of the endpoint nodes indicates how well that model’s spring discharge predictions fit the data.