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Assessing model structural uncertainty: A test case in an alpine karst system

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When disputes arise in the use of groundwater resources, policy-makers increasingly rely on models to make management decisions. However, a plethora of widely different model structures are available, and different conceptual models often explain available observations equally well. In this context, how can modelers support timely decision-making in these complex, uncertain systems? This project tests multi-model ensemble approaches targeted specifically towards decision-support in karst systems. Karst aquifers support roughly a quarter of the global population, yet are challenging to manage because they are both fragile and difficult to model. The discrete, heterogeneous nature of groundwater flow through conduit networks, rather than through distributed pore spaces in sediment, leads to high structural uncertainty. Existing karst models generally either rely on acquiring a detailed conduit network map, or on approximating effective diffuse flow parameters as though water were flowing through a porous medium. Neither of these are adequate for most karst systems, where conduit networks are unmapped, yet flow patterns are fundamentally different from those in porous media.

This project links three existing modeling approaches: 3D geologic modeling with GemPy, an open-source Python package; fracture and karst conduit network generation with the Stochastic Karst Simulator (SKS), a recently published pseudo-genetic structural model; and pipe flow modeling with the US EPA's Storm Water Management Model (SWMM). The study uses pre-existing data from a long-term research site, the Gottesacker Plateau along the German/Austrian border, to investigate different sources of uncertainty in karst groundwater models. Geologic maps, cave system maps, tracer test results, precipitation and spring discharge data, and a previously-developed SWMM model of the site are available.

First, several possible 3D geologic models of the site are developed in GemPy, using only information contained in geologic maps and cross-sections. Each geologic model serves as input to SKS, which uses a Fast-Marching Algorithm to generate many possible conduit network geometries. For each proposed conduit network geometry, several sets of possible hydraulic parameter values (conduit radius and roughness) will also be generated. This will yield an ensemble of competing models, organized into a "model tree" that tracks which geologic model, conduit geometry, and parameter set each model originated from. Next, the likelihood of each candidate model will be assessed by routing flow through the conduits using SWMM, and comparing model-predicted spring discharge timeseries to real discharge data. The artificial geometries yielding spring discharge patterns that most closely match the data can then be compared to the known conduit geometry, to assess the effectiveness of using this approach to identify realistic geometries.

The desirability or undesirability to stakeholders of the predicted spring discharge patterns for each model will be assessed as well. This information can be used to identify the most consequential sources of model uncertainty, as well as to identify what additional data collection would most reduce uncertainty for each stakeholder. In a risk assessment context, uncertainty reduction targeting models of concern (those predicting highly undesirable outcomes) focuses on the uncertainties that matter most to stakeholders, increasing the usefulness of model predictions in the decision-making process.