Sensitivity analysis as essential tool to gain insight into potential hydrological change due to coal development in Australia.

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The development of coal resources through mining or through extracting coal bed methane will potentially affect water resources. Coal bed methane extraction requires the depressurisation of coal seams at depth, the effects of which can propagate through to shallower aquifers and change groundwater levels or surface water groundwater interaction fluxes. Coal mining also has a direct impact on groundwater as coal seams are dewatered for mining. In addition to that, open cut mines intercept rainfall across the footprint of their workings, reducing the runoff to streams.

The Bioregional Assessment Programme is a four year research project to evaluate the direct, indirect and cumulative impacts of coal development across parts of eastern Australia. The Programme identified six bioregions, subdivided into 13 subregions, in which there is the potential for coal resource development. One of the goals of the research is to provide a probabilistic estimate of the change caused by the most likely resource development pathway on water dependent assets in each subregion. Each asset is linked to a set of hydrological response variables, summaries of the hydrology relevant to an asset. Examples of those are the maximum change in groundwater level at an irrigation bore or the change in the number of low flow events in a stream.

The goal of estimating the change in hydrology probabilistically is to fully capture the model predictive uncertainty so as to inform a risk based management of the water resources. This starts with developing a chain of models that is able to numerically simulate the difference in each hydrological response variable between a baseline future and a future with the most likely coal resource developments included. The posterior predictive probability distribution for each hydrological response variable at each location is obtained by integrating the model chain into an approximate Bayesian computation Markov Chain Monte Carlo framework(ABC-MCMC) to constraint the prior parameter distributions with the available relevant observations. While not formally based on the Bayesian likelihood functions, the ABC is preferred as it allows expert knowledge to be included explicitly in the analysis in the absence of sufficient data to establish proper error models for the available observations. In practice, it relies on experts specifying a set of criteria for which model results are deemed acceptable.

The probabilistic, numerical evaluation of predictive uncertainty can however only capture a part of the uncertainty as each numerical model has a set of inbuilt assumptions and model choices that are not straight forward to include in a probabilistic uncertainty analysis. The assessment is therefore complemented by a structured discussion and justification of the main assumptions and model choices in terms of the limiting factors necessitating the assumption (data, resources, technical) and the perceived effect on the predictions.

For the Markov Chain Monte Carlo process, the entire model chain needs to be evaluated 100s if not 1000s of times, which represents a vast computational burden. In addition to that, creating a robust computational framework to integrate a variety of models and run them in sequence is operationally very challenging. For these reasons, in the Markov Chain Monte Carlo process, the original model is replaced with a Gaussian Process emulator. The design of experiment for the training of the emulator is based on a dense Latin hypercube sampling of parameter space. Such emulator can be created for each hydrological response variable at each location very quickly. This allows to tailor posterior parameter distributions to individual predictions with the ABC MCMC.

The parameterisation of the chain of models invariably leads to parameters that have little or no effect on a particular prediction. For this reason, a sensitivity analysis of the design of experiment results is a routine part of the modelling protocol. The main goal is to have a structured procedure in place to guide the prioritisation of factors for inclusion in the Gaussian Process emulators. In addition to that, the sensitivity analysis enables us to focus attention in defining and eliciting prior distributions for parameters. The sensitivity analysis uses the density based sensitivity metrics introduced in Plischke et al (2013). These metrics are augmented with scatter and frequency plots of parameter values versus prediction for selected predictions. These plots both serve as a reality check and to communicate the procedure.

In one of the regions the sensitivity analysis was able to show that both faulting and surface water groundwater interaction, both processes a priori considered to be highly influential on the predictions, were less important than having information on the hydraulic properties of the stressed aquifer or the way the hydrological characteristics of the landscape were captured in the numerical models.

In another region the sensitivity analysis highlighted that the change in groundwater level is mostly affected by the vertical hydraulic conductivity, while the available groundwater level observations to constrain the model were only sensitive to changes in recharge and river bed conductance.

Routinely applying a robust, global sensitivity analysis to the design of experiments proved to provide invaluable insights in the workings of the numerical models and the underlying physical systems. The added value of this understanding is that it, in addition to probabilistically estimating the hydrological change for a specific coal resource development pathway, provides clear guidance for future model development, data collection and monitoring.

References:

Plischke E, Borgonovo E, and Smith CL (2013) Global sensitivity measures from given data European Journal of Operational Research 226, 536-550