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Why and How to Make Hydrological Models Stochastic

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One of the most severe weaknesses of many hydrological models is the lack of considering intrinsic stochasticity.

Even when assuming that hydrological processes are governed by deterministic laws, the fact that such processes are only observable at relatively coarse spatial and temporal scales, and that catchment properties may vary over time (e.g. due to vegetation growth), the hydrological response of a catchment will be different under seemingly identical circumstances. A (hypothetical) reproduction of the rain (at the gauges, with potential differences elsewhere) will thus lead to different internals states (e.g. water content in soil and groundwater) as well as different output (e.g. streamflow). Different states will have consequences on output that go beyond the rain event.

Deterministic hydrological models account for this effect only by superimposing a probabilistic error model to the output of the hydrological model. As the internal states of the model will not change when redoing the simulation, the above-mentioned memory effect is not described by the hydrological model and must be emulated by the output error model (e.g. by using an autoregressive component). As many studies clearly demonstrate, it is very difficult to formulate an output error model that reproduces the statistical behavior of the output to a satisfactory degree.

In the spirit of improving model realism, including the representation of the associated uncertainties, it is more satisfactory to replace such a lumped output error model by a stochastic description of the evolution of the internal states and a simpler output observation error model. We argue that it is advantageous not to make the mass-balance equations of the model stochastic, but to replace constant parameters by stochastic, time-dependent parameters. This leads to stochastic mass fluxes between reservoirs of the model instead of stochastic mass balances. This procedure has four advantages compared to the conventional approach of making mass-balance equations stochastic:

(i) it conserves the mass balance equations;

(ii) it is closer to a mechanistic description, as mass fluxes will become stochastic;

(iii) it makes direct, constructive input for improved model parameterization by providing the opportunity to investigate the correlation of inferred time-dependent parameters on model states and inputs;

(iv) it is easy to adapt a deterministic hydrological model to include this kind of stochasticity.

These properties imply that addressing this model weakness is relatively easy and through property (iii) it provides the opportunity of addressing other model weaknesses as well.

We will outline the theoretical basis of this technique, describe options for the numerical implementation of joint Bayesian inference of constant and time-dependent parameters, present a R package (under development) that supports the implementation, and demonstrate the constructive use of model results for learning about improved model parameterization in a didactical case study based on real data.