Process-informed stepwise multi-variable SWAT calibration framework

Eliana Nervi [a], Rajitha Athukorala [a,b], Floris van Ogtrop [a] and R. Willem Vervoort [a,b]

[a] *School of Life and Environmental Sciences, The University of Sydney, New South Wales, Australia*
[b] *ARC Industrial Transformation Training Centre in Data Analytics for Resources and Environments, Sydney, New South Wales, Australia*
Email: eliana.nervifaggiani@sydney.edu.au

Abstract: Calibrating hydrological models solely to streamflow can erode process realism and limit transferability. One strategy is to use multi-variable calibration and define weighting for the variables, but these are challenging to determine. This ambiguity can be circumvented if the variables are added to the model in a stepwise calibration, based on underlying environmental process. For example, when modelling vegetation, the canopy growth and shadow (LAI) affect ET, and ET has an impact on streamflow. This solution is, however, also problematic, as it is conditioned on the model structure, and landscape models can have a complex structure with numerous parameters. We have demonstrated that using a multi-step framework calibration improves the representation of *Pinus taeda* and grasslands in a SWAT model (Nervi et al. 2025).

Based on our previous results, we explore a further approach to quantify parameter uncertainty and reduce model equifinality in a sequential multi-variable Bayesian inference framework that combines satellite-derived ET and LAI data with observed streamflow data in SWAT, using the Differential Evolution Adaptive Metropolis (DREAM) algorithm. This study aims to quantify and compare the uncertainty (i) a traditional single-objective calibration on flow, (ii) stepwise calibration using SUFI2 (deterministic approach), and (iii) a probabilistic approach using DREAM to identify the posterior for one parameter in the first variable calibration to inform the prior for the same parameter in the second variable calibration sequentially. We apply the framework to a commercially forested small headwater catchment (La Corona, Uruguay), selecting eleven sensitive parameters that influence interactions among vegetation, soil, the atmospheric layer, and flow, and run 13 years of monthly-timestep calibration.

Our results show that flow prediction performance improves using a multi-step framework (ii), with a shift in the parameter distributions and a decrease in SUFI-2 uncertainty compared to calibration on streamflow alone (i). The Bayesian approach using MCMC, coupling SWAT with DREAM resulted in tighter posterior distributions for LAI parameters and improved parameter identifiability. LAI development curve parameters (LAIMX1, LAIMX2) and plant growth-temperature parameters (T_BASE, T_OPT), previously identified as influential in one-at-a-time sensitivity analyses for LAI, became less influential once constrained by literature-informed priors. In contrast, the number of years-to-maturity (MAT_YR) resulted as an important parameter for LAI, impacting the simulated trend significantly. The stepwise calibration using a deterministic approach (ii) remained sensitive to structural ordering (e.g., trade-offs between ET and streamflow) and tended to narrow parameter ranges in early steps (ii). The probabilistic approach using DREAM mitigated this by sampling the full parameter space, using weakly informative (uniform) priors to non-responsive parameters. By developing a process-informed, sequenced posterior-as-prior scheme within DREAM, this workflow aims to strengthen both predictive skill and process credibility, resulting in a transferable template for land-use water-resources scenario analysis.

Keywords: *Multi-variable calibration, Stepwise calibration, SWAT, DREAM*

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