Geophysical Research Abstracts
Vol. 16, EGU2014-2592, 2014
EGU General Assembly 2014

Process Consistency in Models: the Importance of System Signatures, Expert Knowledge and Process Complexity

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Hydrological models are frequently characterized by what is often considered to be adequate calibration performances. In many cases, however, these models experience a substantial uncertainty and performance decrease in validation periods, thus resulting in poor predictive power. Besides the likely presence of data errors, this observation can point towards wrong or insufficient representations of the underlying processes and their heterogeneity. In other words, right results are generated for the wrong reasons. Thus ways are sought to increase model consistency and to thereby satisfy the contrasting priorities of the need a) to increase model complexity and b) to limit model equifinality.
In this study a stepwise model development approach is chosen to test the value of an exhaustive and systematic combined use of hydrological signatures, expert knowledge and readily available, yet anecdotal and rarely exploited, hydrological information for increasing model consistency towards generating the right answer for the right reasons.
A simple 3-box, 7 parameter, conceptual HBV-type model, constrained by 4 calibration objective functions was able to adequately reproduce the hydrograph with comparatively high values for the 4 objective functions in the 5-year calibration period. However, closer inspection of the results showed a dramatic decrease of model performance in the 5-year validation period. In addition, assessing the model's skill to reproduce a range of 20 hydrological signatures including, amongst others, the flow duration curve, the autocorrelation function and the rising limb density, showed that it could not adequately reproduce the vast majority of these signatures, indicating a lack of model consistency. Subsequently model complexity was increased in a stepwise way to allow for more process heterogeneity. To limit model equifinality, increase in complexity was counter-balanced by a stepwise application of "realism constraints", inferred from expert knowledge (e.g. unsaturated storage capacity of hillslopes should exceed the one of wetlands) and anecdotal hydrological information (e.g. long-term estimates of actual evaporation obtained from the Budyko framework and long-term estimates of baseflow contribution) to ensure that the model is well behaved with respect to the modeller's perception of the system. A total of 11 model set-ups with increased complexity and an increased number of realism constraints was tested. It could be shown that in spite of largely unchanged calibration performance, compared to the simplest set-up, the most complex model set-up (12 parameters, 8 constraints) exhibited significantly increased performance in the validation period while uncertainty did not increase. In addition, the most complex model was characterized by a substantially increased skill to reproduce all 20 signatures, indicating a more suitable representation of the system.
The results suggest that a model, "well" constrained by 4 calibration objective functions may still be an inadequate representation of the system and that increasing model complexity, if counter-balanced by realism constraints, can indeed increase predictive performance of a model and its skill to reproduce a range of hydrological signatures, but that it does not necessarily result in increased uncertainty. The results also strongly illustrate the need to move away from automated model calibration towards a more general expert-knowledge driven strategy of constraining models if a certain level of model consistency is to be achieved.