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Interactive Comment

Interactive comment on "Hydrologic predictions in a changing environment: behavioral modeling" *by* B. Schaefli et al.

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Once again, we thank Keith Beven for his critical review of the manuscript and the ongoing discussion, which will undoubtedly help improve the paper. We value Beven's efforts to "stress-test" our proposed approach, and believe that this is a very effective way to achieve clarity and find potential gaps in our proposition. Below, we reply to his second comment, C3550-3552.

1 Where are organising principles useful?

We are a bit surprised by Beven's continued doubt that organising principles may be useful. In our previous reply, we have, in our opinion, given a clear example for the use of an organising principle (maximisation of the net carbon profit, NCP) for predicting the dynamics of water use, CO_2 uptake and certain vegetation properties effectively without calibration.

With our statement that "the likely fidelity of an organizing principle in the landscape depends on the timescale required for it to be expressed, and the time since other effects (humans, glaciation) perturbed it" we tried to make the point that organising principles that explain a trend or end point of a system's evolution do not necessarily tell us how quickly the system evolves and that predictions based on such an end point will necessarily be off by an amount that depends on the time scale of evolution and the time to the last disturbance. Here we define disturbance as an event moving the system further away from its predicted end point. Such an event may either be an external interference such as deforestation or a shift in the boundary conditions that is faster than the time scale of evolution of the system, such as the rapid warming after glaciation.

In the light of the above, Beven's question, "under what range of circumstances might they be useful", can obviously not be answered in general, as it depends on the principle used as well as the time scales of variation of the boundary conditions and the system's degrees of freedom. As an example, the second law of thermodynamics, which tells us something about the equilibrium state of a system and has been proven extremely useful in all kinds of natural science, is not very useful for open systems far away from equilibrium at first sight. However, there is a massive body of evidence suggesting that for open systems far away from equilibrium, the equivalent to the second law may be the maximum entropy production principle, as mentioned in our discussion paper. We are not advocating any particular principle in this paper, we merely outline how such principles could be used for hydrological modelling in terms of formulating falsifiable models and how useful such models could be for prediction if they do turn out to represent the system's behaviour adequately.

2 Constraints and degrees of freedom

The example Beven gave to demonstrate that the proposed principle of maximum NCP may not be useful illustrates a misunderstanding of the proposed optimality approach. Given all the conventional constraints, one has to ask what are the remaining degrees of freedom and what theory can help us predict those. If we "know" things like the nutrient status and plant hormone concentrations that regulate stomata and use these

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as constraints, stomatal conductance may not be a degree of freedom but determined by all of these "constraints". Similarly, if all the vegetation is killed due to an unheard-of drought, a fire, a bulldozer or similar, there are not many degrees of freedom left, so there is no need to look for a theory to explain how they vary. As Beven points out, stomatal closure as a measure to prevent desiccation and plant death can result from the aim to maximise NCP, up to the point where the plant actually dies. There is nothing problematic about this. In fact, one could even predict vegetation death due to an extraordinary event using the NCP maximisation principle. If the vegetation is optimised for a catchment with a certain depth to the water table, a suddenly lowered water table by e.g. ground water extraction could also lead to tree death in the model. This would indicate that the vegetation was not adapted to the conditions it experienced (low water table).

In most interesting cases, there is a considerable number of degrees of freedom that depend on the environmental forcing, e.g. the leaf area dynamics and stomatal conductance in crops between sowing and harvest, the rooting depth in natural vegetation etc. The "legacy of the past" alone will not help us too much to predict those and how they are going to respond to a changing environment. Only if we know the general direction in which vegetation is likely to evolve under any given forcing, can we have hope to make realistic predictions in a changing environment.

3 Circularity

On page C3498 of our previous response, we clarified that we propose two *alternative* uses of optimality principles, "one is to implement organizing principles directly in a model and test the model and the principles by comparison of model output with observations, and the other one is to use an organizing principle to separate out the behavioral models and parameterizations (i.e. the ones respecting this principle) from a

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set of models and parameterizations that equally reproduce the observations." Beven's critique that we run into a circularity if an organsing principle is implemented a priori because "models would then be behavioural in the sense of the authors by definition" may be arising from a confusion about the definition of "behavioural" in the discussion paper. We will clarify in the revised manuscript that our definition of "behavioural" encompasses both, the consistency with observations *and* with a proposed organising principle. This will make clear that in the first use (i.e. implementation of an organising principle in a model and subsequent comparison with observations), the model is only deemed behavioural if it indeed leeds to the desired reproduction of observations, while in the second use, (i.e. calibration to observations and subsequent test for consistency with an organsising principle), the model is only deemed behavioural if it is consistent with the organising principle. We believe that the critique of circularity has no substance in this context.

4 Conclusion

We stand by our opinion that consideration of general organising principles is a promising way forward to make predictions in a changing environment. Keith Beven's comments pointed us to potential for possible misunderstandings and thus will help to further improve the manuscript. However, we wish to emphasise that there may be a fundamental difference in opinion between the authors of this discussion paper and Keith Beven. In contrary to Beven (1993), we do believe "that invalid physical descriptions of real world processes are not useful to the hydrologist." We do not believe that errors in the data resulting in a missing mass or energy balance closure should encourage us not to enforce these fundamental physical principles in the model, or conversely, that a wrong physical description in a model is justified if it allows to reproduce the (potentially wrong) observations. Mimicking past observations cannot be the only aim of a model, as any time series can be reproduced to an arbitrary level of accuracy by a series of

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sinusoidal curves. Particularly in a changing environment, realistic prediction requires knowledge of some general principles that guide the system's evolution.

References

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