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Can we model the hydrological impacts of environmental change?

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Natural and anthropogenic changes constantly impact the environment surrounding us. Available moisture and energy change due to variability and shifts in climate, and the separation of precipitation into different pathways on the land surface are altered due to wildfires, beetle infestations, urbanization, deforestation, invasive plant species, etc. Many of these changes can have a significant impact on the hydrological regime of the watershed in which they occur (e.g. DeWalle *et al.*, 2000; Porporato *et al.*, 2004; Milly *et al.*, 2005; Xu *et al.*, 2005; Poff *et al.*, 2006; Oki and Kanae, 2006; Hayhoe *et al.*, 2007; Weiskel *et al.*, 2007). Such changes to water pathways, storage and subsequent release (the blue and green water idea of Falkenmark and Rockstroem, 2004) are predicted to have significant negative impacts on water security for large population groups as well as for ecosystems in many regions of the world (e.g. Conway and Toenniessen, 1999; Falkenmark, 2001; Johnson *et al.*, 2001; Sachs, 2007). The growing imbalances among freshwater supply, its consumption, and human population will only increase the problem (Vorosmarty *et al.*, 2000). A major task for hydrologic science lies in providing predictive models based on sound scientific theory to support water resource management decisions for different possible future environmental, population and institutional scenarios. But can we provide credible predictions of yet unobserved hydrologic responses of natural systems?

Mathematical models of the terrestrial hydrological cycle are the vehicles that (potentially) enable us to make such predictions (Ewen and Parkin, 1996). These models consist of two elements important for this discussion: (1) model equations (or the model structure), which are the mathematical descriptions of the underlying physical processes; and (2) model parameters, which are the descriptors of the specific physical characteristics of a particular natural system. While most model structures are applicable to a range of systems (e.g. watersheds) with similar dominant processes, most model parameters are specific to a certain system at a certain location (and potentially even at a certain time-period). Assuming, for simplicity, that our knowledge is generally sufficient to select a reasonable model structure to represent a specific natural system (though there might be more than one reasonable choice), then the main task left to the hydrologist is to decide on appropriate model parameters to represent the system at hand. In the case of environmental change impacts, the task is to decide which parameters will change and by how much to reflect the new characteristics of the altered system. This decision requires an understanding of how watershed characteristics relate to model parameters:

$$Model\ Parameters = f\ (Watershed\ Characteristics)$$

i.e. the ability to decide on appropriate model parameters as a function, f, of observable watershed characteristics. The credibility of our change impact predictions thus hinges on how reliably these parameters can be estimated (and how convincingly we can demonstrate this ability).

Most hydrologic models currently used are of the conceptual type in the sense that they spatially aggregate the hydrological processes occurring in the watershed into a number of key responses represented by storage components (state variables) and their interactions (fluxes) (Beven, 2007). Model parameters then describe aspects such as the size of the storage components, the location of outlets, the distribution of storage volumes, relationships between outflow amount and storage content, etc. The large degree of aggregation and conceptualization typically means that these conceptual parameters have to be estimated through calibration, i.e. a process in which model parameters are adjusted until the model simulations match historical system input/output observations. If observations of streamflow (the main variable used for calibration) are available at the watershed outlet, then lumped parameters can be calibrated at the appropriate scale. If such observations are not available, as in the case of environmental change predictions, then our predictions are typically very uncertain, and the credibility of our model result suffers.

If streamflow observations are not available, then two alternative approaches have been used: the estimation of *a priori* parameter values for conceptual model structures from soil and vegetation data (e.g. Atkinson *et al.*, 2003; Koren *et al.*, 2003), or the use of a regionalization approach (e.g. Bloeschl, 2005). The objective of regionalization is to derive empirical (regression) relationships between individual model parameters and physical watershed characteristics at the watershed scale. The parameters are estimated through calibration in a large number of gauged watersheds and regressed against physical characteristics of these watersheds. If one (or more) of the regionalized parameters is (are) related to a characteristic that is affected by the environmental change addressed, e.g. percentage forest cover, then these regression equations could be used to estimate the change impact as expressed by the value of the parameter. While this approach, in theory, produces equations that allow for the estimation of effective watershed parameters at the watershed scale, it is hindered by several issues (Wagener and Wheater, 2006). A main problem is that the parameters are estimated in a set (rather than individually), but then regionalized individually. Also, most automatic calibration procedures used do not consider the specific hydrological function of each parameter, but rather, minimize some overall measure of the residuals. There is little reason why most automatic calibration approaches should result in hydrologically realistic parameters that are independent of the other parameters in their set. Manual calibration approaches, on the other hand, often attempt to cause model components (and, therefore, individual parameters) to mimic the processes they are designed to represent, and they concentrate on having each parameter serve its primary function rather than overall model performance. Such an approach might lead to more "hydrologically realistic" parameters, but we have yet to translate these ideas into an appropriate automatic procedure (though multiple attempts have been made). Other problems like model structural error and limited predictive power of many observable watershed characteristics during regression (e.g. lack of good sub-surface descriptors) add further uncertainty to this approach (Wagener *et al.*, 2004).

The search for an ability to predict environmental change impacts was one of the main drivers for the development of spatially distributed physically based hydrological models (Refsgaard *et al.*, 1996). These models, at least in theory, derive both their model equations and their model parameters from physical watershed characteristics, and do not require model calibration. However, parameterization of these physically based models using physical system characteristics only is difficult since bulk properties of the hydrological system have to be estimated at model element scales usually exceeding our measurement scale. Approaches to *a priori* parameter estimation for physically based model structures (and often, also for conceptual ones), for example, commonly utilize pedotransfer functions to estimate soil hydraulic parameters. These estimates are likely to be not very accurate descriptors of the watershed model parameters needed at the model element scale, and should therefore be treated as uncertain (see discussion in Beven, 2001). Parkin *et al.* (1996) tested a physically based model parameterized using *a priori* estimates only and found that their streamflow predictions contained considerable uncertainty.

The performance of both conceptual and physically based modelling approaches when using a priori parameter estimates therefore, depends on the degree of correlation that can be achieved between model parameters and observable watershed characteristics. On the basis of those analyses that included uncertainty in any of the approaches discussed above, it is likely that both, *a priori,* and regionalized parameter estimates, will lead to predictions with considerable uncertainty associated with them. Additional constraints will thus often (always?) be required to reduce the number of feasible simulations (and therefore, parameter sets).

Rather than accepting the uncertain predictions derived when sampling from uncertain priors, we can look for additional constraints to put on our models. Such constraints can be derived from physical or empirical relationships about how watershed response characteristics relate to physical watershed or climatic characteristics (Allen and Ingram, 2002; Yadav *et al.*, 2007). One physically based example for a relationship of this kind is the Budyko curve, which relates climate (potential evapotranspiration over precipitation) to the runoff ratio (runoff over precipitation) at longer time scales (Budyko, 1974). While different studies have shown that physical watershed characteristics

such as soil water-holding capacity and vegetation cover might also be important, and that considerable scatter around the basic relationship exists (Sankarasubramanian and Vogel, 2003; Donohue *et al.*, 2007), this relationship can place constraints on acceptable water balance simulations. Other hydrologic indices, reflecting other aspects of the streamflow hydrograph, can similarly be regionalized and used as additional constraints. The individual relationships will still be uncertain and the constraining achieved using a single relationship might not be very large. However, formalizing what we know regarding such relationships (including the uncertainty in this knowledge), and rejecting all those *a priori* feasible parameter sets that produce simulations which conflict with this knowledge, might lead to considerably less uncertain predictions (Wagener *et al.*, 2007). Much more information might be available to reduce predictive model uncertainty if it is formalized, potentially leading to an increased credibility of environmental change predictions.

In Summary

- **Credible modelling of environmental change impact requires that we demonstrate a significant correlation between model parameters and watershed characteristics, since calibration data are, by definition, unavailable.**
- **Currently, such *a priori*, or regionalized parameters estimates, are not very accurate and will likely lead to very uncertain prior distributions for model parameters in changed watersheds, leading to very uncertain predictions.**
- **Other constraints have to be invoked to reduce this uncertainty.**
- **One way to do so is to formalize physical or empirical relationships between watershed response characteristics and physical watershed or climatic characteristics, including their uncertainty.**
- **Using several such constraints might often allow us to reject many *a priori* feasible parameter sets which result in predictions that conflict with these relationships and considerably reduce predictive uncertainty.**

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