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# Hydrologic predictions in a changing environment: behavioral modeling

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## Abstract

Most hydrological models are valid at most only in a few places and cannot be reasonably transferred to other places or to far distant time periods. Transfer in space is difficult because the models are conditioned on past observations at particular places to define parameter values and unobservable processes that are needed to fully characterize the structure and functioning of the landscape. Transfer in time has to deal with the likely temporal changes to both parameters and processes under future changed conditions. This remains an important obstacle to addressing some of the most urgent prediction questions in hydrology, such as prediction in ungauged basins and prediction under global change. In this paper, we propose a new approach to catchment hydrological modeling, based on universal principles that do not change in time and that remain valid across many places. The key to this framework, which we call behavioral modeling, is to assume that these universal and time-invariant organizing principles can be used to identify the most appropriate model structure (including parameter values) and responses for a given ecosystem at a given moment in time. The organizing principles may be derived from fundamental physical or biological laws, or from empirical laws that have been demonstrated to be time-invariant and to hold at many places and scales. Much fundamental research remains to be undertaken to help discover these organizing principles on the basis of exploration of observed patterns of landscape structure and hydrological behavior and their interpretation as legacy effects of past co-evolution of climate, soils, topography, vegetation and humans. Our hope is that the new behavioral modeling framework will be a step forward towards a new vision for hydrology where models are capable of more confidently predicting the behavior of catchments beyond what has been observed or experienced before.





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# 1 Introduction

## 1.1 Hydrologic change – the prediction challenge

The world is presently experiencing rapid and large scale modifications of the land surface (e.g. deforestation, urbanization) and changes to the climate. In the context of this ongoing global change, understanding and predicting the related hydrologic changes is one of the most urgent questions that hydrologists face today (Barnett et al., 2008; Stonestrom et al., 2009; Blöschl and Montanari, 2010). Perhaps the greatest challenge comes from the fact that the consequences for hydrology will arise from both changes in the forces acting on the landscape (climate, land management), and from the way change is transmitted through the various associated systems and subsystems. As a result, both the ecosystem structure (e.g., vegetation patterns, drainage network, soil properties) and its hydrologic response (e.g., water balance, extremes) undergo modifications. For example, in Alpine catchments where the glaciers are gradually disappearing due to a warmer climate predicting the consequences for discharge (e.g. Horton et al., 2006; Huss et al., 2008) involves predicting how fast and to what extent the ice may melt, how vegetation may evolve on the newly ice-free surfaces, and how the rainfall-runoff behavior regime is modified in the "new" catchment that emerges as a result. As the ice melts away in these catchments, weathering and new erosion processes emerge on the moraines exposed to the atmosphere, vegetation succession occurs, new vegetation emerges and accesses different soil moisture compartments, soil structure as well as soil biology changes as a result of modified hydric conditions. In short, all biotic and abiotic components of the ecosystem are undergoing simultaneous, interdependent changes.

## 1.2 A challenge to the status quo

These interdependent changes present a fundamental challenge to the way predictions are typically made in catchment hydrology. The most common approach adopted





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in present-day change predictions is the adoption of likely or alternative future "scenarios" regarding climate, land cover or land use, and other hydrological parameters (Mahmoud et al., 2009). The structure of the catchment ecosystem is considered essentially as fixed, with climate as an exogenous forcing (akin to solving a boundary value problem). In the Alpine example above, the future scenarios could specify the extent of glaciers and of forested areas under climate change, chosen to represent likely future conditions in a seemingly plausible way. A typical approach to assigning plausible future values to model parameters and forcings is the use of external (not coupled) model outputs (e.g., global climate models, land use evolution models) or the use of expert judgment. The likely impacts of these change scenarios on hydrological responses are then evaluated using models developed for the present or past conditions.

The following two examples illustrate the scenario-based approach to hydrologic prediction. Zierl and Bugmann (2005) simulated the future hydrologic responses of Swiss Alpine catchments under global IPCC (Intergovernmental Panel on Climate Change) land use change scenarios using a physically-based ecohydrological model. They decreased forest cover in valley bottoms and increased forested areas close to the timberline without, however, considering the evolution of the timberline itself due to projected climate change. Schaefli et al. (2007) created future scenarios of glacier surface area using an empirical relationship with snow accumulation area, and simulated the resulting precipitation-runoff transformation with a conceptual hydrological model. Apart from updating the glacier surface, all other model parameters, such as those relating evapotranspiration to soil moisture were kept unchanged, even though in reality the vegetation composition is highly likely to change.

If we attempt to predict long-term hydrologic change where both the landscape structure and the hydrologic response evolve, feeding back on each other, then past response alone cannot be a sufficient guide to future response, and current hydrologic behavior (including both landscape structure and hydrologic response) cannot readily be extrapolated to predict future behavior, such as through the use of assumed future





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change scenarios. Such scenario-based predictions can only be seen as informed guesses, producing rough estimates of possible future conditions, accounting only partially for likely directions of natural and anthropogenic ecosystem evolution.

An alternative approach is to broaden the prediction problem to the coupled modeling of the landscape structure, the climatic drivers and the hydrologic response, including the feedbacks resulting from their co-evolution. This approach has long been recognized in climate and earth system sciences, and has motivated the development of several fully-coupled, highly detailed, physically-based land-atmosphere or earth system models that aim to include all relevant biological, geomorphologic, pedologic, hydrological and meteorological processes and appropriate initial and boundary conditions (e.g. Doherty et al., 2000; Levis et al., 2004). In this type of model, the ecosystem (both structure and response) evolves as a result of interactions and feedbacks between all the encoded (hydrological, land forming and life sustaining) processes.

The trajectory of ecosystem evolution in these highly complex coupled models depends very much on the realism and accuracy of the various process descriptions and the associated parameter values. Under these circumstances, what confidence do we have that such predictions turn out to match reality, or even come close to what might actually happen in the future? The descriptions of individual processes, process interactions and feedbacks are intrinsically imprecise and uncertain, and may highly depend on initial conditions, which are also possibly unknown.

### 1.3 A way forward

In this paper, we present a possible new approach to hydrologic predictions, which we call behavioral modeling. This new approach presents an elegant way forward to critically learn from observations of past behavior to predict future behavior in probabilistic terms, i.e. to use understanding of past behavior to choose amongst many possible trajectories of future system evolution. The rationale of this new approach, which will be elaborated in more detail in the remainder of this paper, can be summarized as follows: The current structure of an ecosystem is a legacy of its historical evolution,



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and therefore contains information about that evolution, which we can potentially summarize in terms of (an) organizing principle(s). This principle, in turn, can potentially be used to develop a predictive framework that combines it with observed data and any other prior knowledge. In this sense, the organizing principle acts as a "likelihood function": it tells us which, among all physically possible outcomes (given conservation laws of mass, momentum and energy, as well as local constraints), are the most probable ones.

Section 2 of this paper elucidates the rationale and fundamental assumptions of the proposed approach. We then discuss the nature of the organizing principles in more detail (Sect. 3), drawing on examples in the literature where these principles have already been identified and applied. In Sect. 4 we describe the practical application of the approach and its relationship to established modeling approaches and other usages of the term *behavioral* in hydrology. We use examples to illustrate the major challenges involved in developing such a new modeling framework, and the open science questions that need to be addressed as we proceed in this direction (Sect. 5). We conclude (Sect. 6) by providing a perspective on possible ways forward to achieve these goals.

## 2 Predicting hydrologic change: behavioral modeling

### 2.1 The structure problem

Hydrologic predictions at the catchment scale are hampered by what we call the "structure problem": the difficulty to provide a mapping between the catchment's biogeomorphic structure exerting a dominant control on the hydrological processes and the necessary model structure to predict these processes (i.e., to extrapolate them in space or in time).

This structure problem manifests itself differently for different model types. Prediction methods of the bottom-up type rely on physical descriptions of all relevant processes; detailed knowledge of the topology/connectivity of surface and subsurface flow paths is crucial to predicting storage, release and redistribution of water, dissolved mass, and energy within the system. Such bottom-up models suffer from the fact that current technologies do not enable us to observe these structures and associated hydrologic processes in situ everywhere.

An alternative, top-down, approach is to infer dominant catchment structures from data by attempting to reproduce observed integral responses, such as residence time distributions of water leaving the catchment as expressed in the form of the hydrograph – or in the form of tracer breakthrough curves. Due to their integral nature, such signals are of "low dimension", and the inference of model structures from such integral catchment responses suffer from "equifinality" and uncertainty: several types of model structures chosen to reflect the bio-geomorphic structures in the landscape may yield the same integral response. This is a serious drawback when one considers the fact that in a changing environment the catchment architecture can be expected to also evolve due to changes in the system boundary conditions.

## 2.2 Structure and organization in catchments

Many researchers in the hydrologic community have come to the realization that a possible way to overcome both "structure" problems mentioned above is to add an intermediate level of abstraction that helps connect landscape structure to model structure, for example using the concept of hydrologic ecosystem functions, which is receiving increasing interest in hydrology (Sivapalan, 2005; Wagener et al., 2007).

Following Black (1986), Wagener et al. (2007) define the hydrologic functions of a catchment as consisting of partitioning, storage (retention) and release of water (Fig. 1a), and suggest that we need something more than mere small scale process descriptions to fully capture these essential and universal functions. This is because they arise as emergent behaviors from the natural organization of the catchment structure, linked by interactions and feedbacks to other land forming and life sustaining processes occurring within the ecosystem (e.g. Lin and Chen, 2006; Sidle and Onda, 2004; Paola et al., 2006; Kumar, 2007), including the role of humans (Fig. 1b).





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This complex interplay between biotic and abiotic processes shapes the constantly evolving landscape; whatever properties it has today are the legacy effects of the history of its evolution. The structure of the landscape (e.g. vegetation patterns, river networks, soil catena) suggests that these interactions of climatic, geomorphic, pedological, biological and hydrologic processes is not unorganized but indeed leads to specific, identifiable patterns (e.g. Rietkerk and van de Koppel, 2008). The mechanisms underlying the observed patterns and functions of catchments and associated ecosystems and their connection across time, space and scale are the subject of intense research (e.g. Levin, 1992; Rodriguez-Iturbe et al., 1992a; Thomas, 2001; Gisiger, 2001; Sivapalan, 2005), and a range of models that reproduce observed patterns and feedbacks are available (see e.g. Borgogno et al., 2009; Rodriguez-Iturbe et al., 2007). Saco et al. (2006), for example, present a model that, in water-limited ecosystems, reproduces observed patterns of vegetation, runoff, erosion and their redistribution, and the evolution of micro-topography. Conversely, it is reasonable to expect that observable patterns of vegetation and micro-topography contain valuable information and may provide insights into the interactions and feedbacks between the water flow and evolutionary land forming and ecological processes that they emerge from (e.g. Grimm et al., 2005).

### 2.3 Using organizing principles to constrain models

From this perspective, it is tempting to think that the organized patterns that we see in the landscape could be translated into certain principles that may underpin these emergent patterns and encapsulate the nature of system evolution, in the future as well as in the past.

In the words of Rinaldo et al. (2006), "nature works through imperfect searches for dynamically accessible optimal configurations". If we can discover and summarize the underlying principles in terms of rules or governing laws (Paik and Kumar, 2010), we could mimic this search in our models and identify plausible (future) system states respecting these principles as well as any other boundary conditions or constraints that may apply. We call these governing laws "organizing principles" (a term that is





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becoming increasingly popular in the literature, e.g. McDonnell et al., 2007; Wagener et al., 2010), and the plausible states "behavioral" – in analogy to the usage of this term in systems theory, where "behavioral" designates a subset of all theoretically possible dynamic system outcomes that is actually observed. Polderman and Willems (1998) give the example of planetary orbits to illustrate this concept. Since the time of Kepler we know that they are elliptic. The general equation describing the movement of two bodies mutually attracted by gravitation would also allow hyperbolic paths but they would not be "behavioral", and are eliminated. A hydrological example can be found in Ridolfi et al. (2006): they describe a riparian water table – vegetation feedback system that theoretically has two stable states, complete vegetation cover or complete absence of vegetation, but the non-vegetated state is rarely observed in nature, i.e. therefore it is not behavioral.

As mentioned earlier, the evolution of a catchment ecosystem could, in theory, be predicted by modeling all relevant process interactions with suitably complex models. However the uncertainty in the model structure and parameters limits our ability to make reliable predictions with such models. An infinite number of trajectories of system evolution may be possible in the future, and there is a clear need to discriminate amongst these and choose only those that are plausible. If we adopt a priori the organizing principle that encapsulates or drives some of these interactions, we can then account directly for their joint effect on the overall system behavior by adjusting the model structure and parameters so as to respect this organizing principle.

## 3 Identifying organizing principles

An organizing principle may be seen as the answer to the question: "In a landscape where every component is permanently changing, is there some principle that nevertheless persists and continues to manifest itself in the evolving features of this dynamic system?" This general definition is indeed very broad and leaves space for a large range of potential organizing principles that either reflect the causes of evolution or the





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resulting signatures (for a short discussion of these points of view, see Paik and Kumar, 2010).

The use of organizing principles is predicated on the idea that there are certain configurations of the system that are more likely to occur than others. These "stable states" should not be confused with the notion of equilibrium or steady-state. Environmental systems are non-equilibrium systems by definition, and moreover are almost never observed in a "steady-state".

Two broad classes of organizing principles can already be found in the hydrologic literature: optimality principles and empirical patterns.

### 3.1 Optimality principles

*Optimality modeling* is a technique which first became popular in behavioral ecology to predict the behavior of animals given all factors and constraints facing them (see, e.g. Krebs and Davies, 1993). A recent example is the prediction of bird migration routes on the basis of optimal trade-offs between travel time and energy-use (Vrugt et al., 2007).

A special issue of Philosophical Transactions of the Royal Society, B-Biological Sciences, edited by Kleidon et al. (2010), provides overviews of physical concepts underpinning optimality, such as maximum entropy production (Kleidon et al., 2006; Kleidon and Schymanski, 2008; Ozawa et al., 2003), minimum energy expenditure (Rodriguez-Iturbe et al., 1992b; Rinaldo et al., 1992) or Helmholtz free energy dissipation (Zehe et al., 2010). Paik and Kumar (2010) discuss a range of optimality principles that can be used to interpret observed landscape patterns or to predict land forming processes and the resulting patterns.

In the case of biotic systems, optimality principles can be formulated on the basis of established biological laws, such as Darwin's theory of evolution. A listing of evolutionary organizing principles in plant sciences can be found in the review by Schymanski et al. (2009a). The most well known example in hydrology is the use of ecological optimality principles by Eagleson (Eagleson, 1982, 1978; Eagleson and Tellers, 1982) who focused on net primary production. In more recent ecohydrological studies, we have seen the introduction of several other alternative organizing principles such as the maximization of water use, the minimization of water or oxygen stress (e.g. Brolsma and Bierkens, 2007; Marani et al., 2006b; Porporato et al., 2001; Rodriguez-Iturbe et al., 1999; Caylor et al., 2009), and the maximization of net carbon profit: Schymanski et al. (2007, 2009b) simulated the most probable vegetation cover in catchment ecosystems as the one that maximizes the long-term net carbon profit for a given climate, subject to local constraints. They obtained good correspondence between transpiration fluxes observed under the given climate and the corresponding simulated flux for the most probable vegetation cover (see Fig. 2).

### 3.2 Empirical patterns

The above optimality-based organizing principles result from a priori knowledge and assumptions about the underlying physical and ecological principles. However, we can also formulate organizing principles that are empirical, i.e. based on the patterns of the behavior of natural systems observed at many places, scales or moments. Such empirical principles or laws can be used for predictions only after they have been extensively shown to be time-invariant and valid at many places and scales.

A good example of such an empirical organizing principle in hydrology is the Budyko curve (Budyko, 1984), which is a widely known and accepted universal pattern related to the climate dependence of the annual water balance. In the Budyko diagram (Fig. 3), in theory, the ratio of annual evapotranspiration to precipitation can take on any value below the straight line envelopes, and yet values near the empirical Budyko curve are deemed the most probable, or in other words behavioral. In this sense, the Budyko curve is a potentially useful concept to discriminate between likely and unlikely catchment annual water balance responses. For example, Li (2010) used the Budyko curve to discriminate between unlikely and likely parameter combinations (climate, soils and topography) for a physically-based, high resolution, spatially distributed hydrological model.

Hydraulic geometry relations can be seen as a widely-used form of a behavioral model. An early example is Lacey (1930) who found a simple equation relating the width of a natural channel at bank-full discharge to the square root of flow. As pointed out by Savenije (2003), many authors have confirmed this simple formula without being able to give a physical (causal) explanation. Savenije suggested that Lacey's formula emerges from the "bed-shaping flow velocity that has just sufficient power to lift the bottom material to the natural levee". The existence of such relationships implies that there may indeed be organizing principles that are useful for making predictions about whole system behavior at ecosystem level, which have not yet been shown to reflect a classical (i.e., physical or biological) law or related optimality principle.

### 3.3 Use of modeling to develop organizing principles

As the evolution of natural systems is often very slow, we can rarely observe it. Therefore, a promising approach is to translate the observed behavior into a model and to let the model shed light on the evolution and on potential stable states. An example can be found in Wong (2008): Analyzing the effect of overland flow regime on detention storage, Wong found that the dominant flow regime in nature is the one that provides maximum flood attenuation. Another example is the work of Ridolfi et al. (2006) (see also Sect. 2.3): They formulated a simple model of water table – vegetation dynamics in riparian zones and identified several theoretical stable states depending upon the initial water table depth. They argued that one of the stable states (corresponding to absence of vegetation) is rarely observed in nature and discuss how to make use of their results to quantify ecosystem resilience.

Such ecosystem resilience could itself be used as an organizing principle to build predictive models. In fact, resilience is a classical landscape sensitivity concept that designates the likelihood of a change, which is widely used in geomorphology and in ecology (e.g. Usher, 2001). In ecology, the sensitivity concept takes on different forms, such as elasticity, extinction risk, persistence, population viability, resilience, resistance, or turnover time (Miles et al., 2001). These results point towards potentially new experimental and modelling approaches that can be adopted for discovering new organizing principles, as articulated by Kleinhans et al. (2010).

## 4 Behavioral modeling in practice

### 4.1 How do we build behavioral models?

Building a hydrologic prediction model within the behavioral modeling framework involves the following steps: (i) understand current or potential stable system states resulting from the co-evolution of interacting processes; (ii) summarize this understanding in some time-invariant organizing principle useful for hydrologic prediction at many places, scales and times; (iii) build a model to simulate a range of different system behaviors; (iv) use the organizing principle to identify the most probable system behavior, i.e. to identify the most appropriate model parameterization for a given case study; (v) validate or falsify the model.

Understanding and identifying stable system states and organizing principles, from models or from observed data, requires of course, much further research. As we will illustrate in the next section, steps (iii) to (v) can be completed at least partly with existing models and model identification techniques (see, e.g. Gupta et al., 2005).

The validation and model falsification steps are an essential component of the behavioral modeling framework. Potentially available observed data about system structure and response is not used to calibrate or constrain the hydrological model, but rather used to falsify the assumed organizing principle, which offers new perspectives for the development of specific model validation techniques.

Going back to the examples of Schymanski et al. (2008, 2009b), the authors postulated that vegetation at the landscape scale maximizes net carbon profit. Accordingly, they developed a water balance model that included a conceptualization of all key processes involved in terms of plant physiological behavior and their carbon costs and benefits and thereafter optimized the model parameters so as to maximize net carbon





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profit. Therefore, the resulting model parameters were obtained thanks directly to the organizing principle without calibration to match observed evaporation or other fluxes. The comparison of the fluxes predicted by this optimal model against observations then becomes an exercise in falsification of the hypothesis that plants maximize net carbon profit.

### 4.2 Relation to existing modeling approaches

Traditional prediction models in catchment hydrology are developed using either a bottom-up or a top-down approach (Sivapalan, 2005, see also Fig. 4a). As illustrated in Fig. 4b, the behavioral modeling framework can be seen as an extension of this traditional framework, where the organizing principle is used to identify the most appropriate model (structure). Because a model of hydrologic change must account for structure forming and life sustaining processes in the landscape, one would normally expect them to be more complex and multi-dimensional than traditional hydrological models. The use of organizing principles, however, contributes to model parsimony: as Marani et al. (2006a) state in the context of developing a coupled, predictive model of vegetation and geomorphology for tidal ecosystems, the key is the "identification of simplified formulations of the relevant biophysical interactions, yet retaining their essential dynamics". The organizing principle, in turn, would have been previously identified based on theory and data. For example, the Budyko curve, as an empirical organizing principle, results from theory (envelop lines), as well as from observed data. As in a traditional modeling framework, the model predictions are compared to theory and to observed data to validate the modeling assumptions.

On the basis of the above discussion, one may be tempted to think that the development of behavioral models is way too far into the future. In reality, though, many behavioral models are already in place although they are not yet called that. As example, we would like to present the results of a modeling study (representing the bottom-up approach) that, in our view, is just a small step away from using organizing principles for hydrologic predictions.





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Hwang et al. (2009) use a complex physically-based model (the RHESSys model Band et al., 1993; Tague and Band, 2004) to investigate whether the observed ecosystem patterns in a fully forested catchment of the Southern Appalachian Mountains correspond to some optimal configuration under the local climate and soil conditions. They asked the question whether the catenary sequence of ecosystem patches maximizes a catchment scale vegetation property such as Net Primary Production (NPP). Hwang et al. (2009) first calibrated the hydrological model parameters to yield maximum correspondence between observed and simulated daily runoff. They then varied the average rooting depth and the spatial arrangement of rooting depths (i.e., from increasing in hillslope direction to uniform and then to decreasing in the hillslope direction) to yield maximum correspondence between observed and simulated above ground vegetation (in terms of leaf area index). Subsequently, they showed that the same rooting depth distribution parameters that led to an optimal correspondence between simulated and observed runoff also maximizes catchment scale NPP (compare Fig. 9b and Fig. 11a of Hwang et al., 2009).

In the discussion of their results Hwang et al. (2009) argue that the observed vegetation gradients do correspond to some optimal state of system-wide carbon uptake (Hwang et al., 2009, Sect. 5.1). From a behavioral modeling perspective, we understand this to mean that they have found evidence that maximization of NPP can be used as an organizing principle to make predictions about spatial vegetation patterns and coupled ecohydrologic response. In other words, their results suggest that they could calibrate their detailed process model by simply maximizing NPP, i.e. to ensure that the model satisfies the identified organizing principle. Then, the simulated and observed patterns could be used to validate or falsify the assumptions in the model.

This offers some new perspectives for change predictions too: for example, if they were to investigate system behavior under changed climate, they could directly infer the future vegetation patterns along with the future hydrologic regime through invoking the organizing principle alone, assuming that it is both universal and time invariant. This, in our view, would represent a considerable advance over scenario-based predictions,





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i.e., simply feeding assumed climate change scenarios into a present-day hydrological model.

**Relation to other "behavioral model" concepts**

Hydrological modeling has a long tradition of parameter estimation and model identification. In this context, Beven and Binley (1992) shaped the usage of the term "behavioral parameter sets" for sets that, within a chosen model structure, give acceptable reproductions of the observed behavior. This usage goes back to Hornberger and Spear (1980) who suggested "(...) that the result of any simulation using a model can (...) be classified as exhibiting either 'the behavior' or 'not the behavior' (of the system)" (Hornberger and Spear, 1980, p. 30) and led to the expression "behavioral model" (Beven, 2006). Just as in our proposed framework, Beven's use of the concept "behavioral" designates, in the traditional model development context, a subset of all possible models that is plausible given the historical behavior of the studied system. There is, however, a fundamental difference of how behavioral models are obtained. The traditional approach compares the simulated variable (e.g. discharge) to observed values (time series) of the target variable to select behavioral parameter sets or model structures. This selection is based on a performance measure that can be either a classical sum-of-squared error measure or any other distance measure (see, e.g. Schaefli and Zehe, 2009). The retained models are, thus, the ones that best mimic historical records of the variable to be predicted.

Behavioral modeling uses a priori knowledge and historical behavior to propose an organizing principle to identify behavioral models. The method of identification depends on the type of organizing principle. In the case of optimality principles, a behavioral model simply maximizes the corresponding system output. The fundamental difference to Beven's concept lies in the fact that in behavioral modeling, the identification of behavioral models involves deeper insights into the system dynamics and explicitly excludes comparing the target variable (which we want to predict) to observations of





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this variable – this as a prerequisite to use such observations to validate or falsify the model, i.e. to hypothesis testing.

## 5 Potential of the new approach

The behavioral modeling approach is based on explicit hypotheses about the functioning and directionality of evolution of whole ecosystems. Therefore, we believe it has great potential for the prediction of hydrologic change and much of the present paper argues along this line. Hereafter, we would like to discuss some additional promising aspects.

The proposed modeling framework represents a major step towards the building of models based on understanding rather than on calibration to detailed local observations. This goes to the heart of the philosophy adopted by the predictions in ungauged basins (PUB) initiative (Sivapalan, 2003). In this context, the organizing principles represent the crystallization of our understanding of how nature works and offer a new way to transfer knowledge of ecosystem functioning from one place to another.

Organizing principles encapsulate how small scale process interactions are related to the system evolution and response at some higher scales. They thus provide a link between the scale of prediction (e.g. the catchment scale) and the scale at which the relevant processes interact. As example, we can cite here the organizing principle proposed by Zehe et al. (2010). They propose maximum energy dissipation as a connection between worm burrow density and rapid water flow at the hillslope scale. In this sense, we can see that the investigation of organizing principles through virtual and real-world experiments, including controlled field or laboratory experiments, offers new perspectives towards mapping of relevant structures across scales.

The use of organizing principles also presents a new way of including more process understanding into hydrological models and for transferring understanding across different types of models. We can, for example, gain knowledge about the sensitivity of riparian ecosystems to water table depth from a simple physical model (see Ridolfi et al., 2006), translate it into an organizing principle (e.g., "maximization of resilience") and then use it to parameterize the vegetation cover (i.e. to identify the most likely vegetation state) in a more complicated hydrologic prediction model. Nicotina et al. (2010) use the principle of minimum energy expenditure, combined with a physical model, to identify equilibrium soil depths to be used in a rainfall-runoff model. In this sense, behavioral modeling has the potential to help unify (data-based) conceptual and physically-based modeling approaches.

Finally, a behavioral model can be viewed as a hypothesis about how a catchment ecosystem works. Since it provides quantitative predictions, the validity of the hypothesis can be tested by comparing the predictions against observed system responses (discharge, evaporation etc.). Our understanding advances, even if, and especially when, an organizing principle is proven to be false. This offers an important advantage over traditional models where the observed system response is used for model calibration and is difficult to use for further hypothesis testing, i.e., there is usually no generalizable hypothesis to test.

## 6 Conclusions

This paper has presented the rationale for a new behavioral modeling framework for hydrologic prediction that makes use of universal and time-invariant organizing principles to at least partially replace calibration to observed response data as in traditional models. Our hope is that this modeling framework will contribute to the development of a new generation of models that can be extrapolated in time and in space, and that open new perspectives for hypothesis testing and for unifying traditional conceptual and physically-based modeling approaches. It is a small step towards a new vision for hydrology: one in which there are less black-box parameters, where models are driven both by information about particular places and by fundamental understanding encapsulated in universal principles. It therefore heralds a new future for hydrology where hydrologic models are capable of more confidently predicting the response of





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a catchment to conditions that have not been experienced in the past, such as under climate or land-use change.

The key to this framework is to postulate that we can use organizing principles to identify the most probable behavior of a catchment ecosystem and the related most appropriate model structure and response. The proposed framework can be viewed as a generalization of optimality modeling, as the time-invariant organizing principles can either be derived from fundamental physical or biological laws (as in the case of several optimality hypotheses currently being explored), or from empirical laws that have extensively been shown to be time-invariant and to hold at many places and scales. The proposed framework aims at overcoming the need of observed data for model calibration and can be used as hypothesis testing tool when used in conjunction with available data.

There are, of course, an enormous number of open questions and to make progress in this direction, much further research is required: what types of organizing principles are useful for hydrologic prediction? Are they transferable, i.e. are they useful for predictive model development in many places? Can we classify catchments with the help of organizing principles? How can we know whether an ecosystem is in a stable state? How can we know how long it takes before a system reaches a new stable state?

Behavioral modeling should be viewed as a modeling technique, as a way of formulating modeling hypotheses and translating them into mathematical models (rather than as a “literal transcription” of what nature actually does). Unlike traditional approaches to modeling, where calibration rules the day, model building and model validation in the behavioral framework is really, in one way or the other, a hypothesis test. When a model constrained by an organizing principle fails to reproduce real-world observations, this in itself represents scientific progress as it helps eliminate inappropriate assumtions or model structures. Or, in other words, as Kull (2002) formulates it, “poor results (...) are not proof that optimality fails; they merely imply that the function to be maximized in a natural community remains undiscovered.”





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Building hydrologic models thus becomes a process of formulating hypotheses about the organization and structure of the landscape – hypotheses that will need to be tested by new observations and new field experiments. It will thus require an interdisciplinary research effort that brings together specialists from many different fields related to catchment and ecosystem functioning, motivated by both the desire to discover and test widely applicable organizing principles and by the need to make hydrologic predictions in specific places about future conditions.

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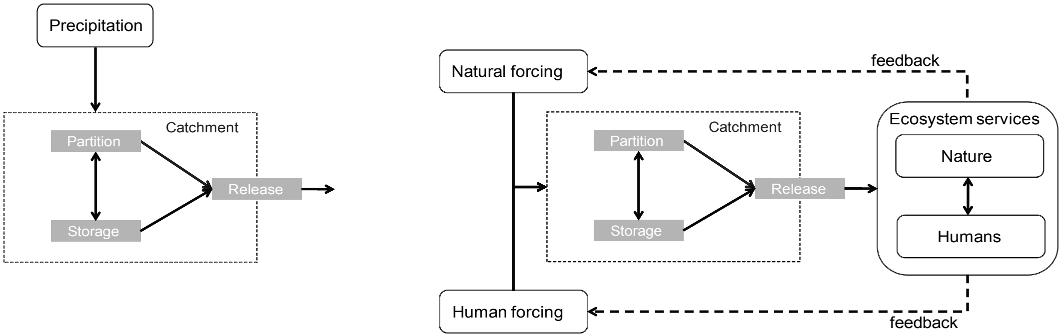


**Fig. 1.** Left: The catchment and its function, viewed as a system with fixed structure and precipitation as exogenous forcing (adapted from Wagener et al., 2007, with the permission of the authors). Right: the catchment as part of an evolving ecosystem, which provides services and feeds back on the human and natural forcing.





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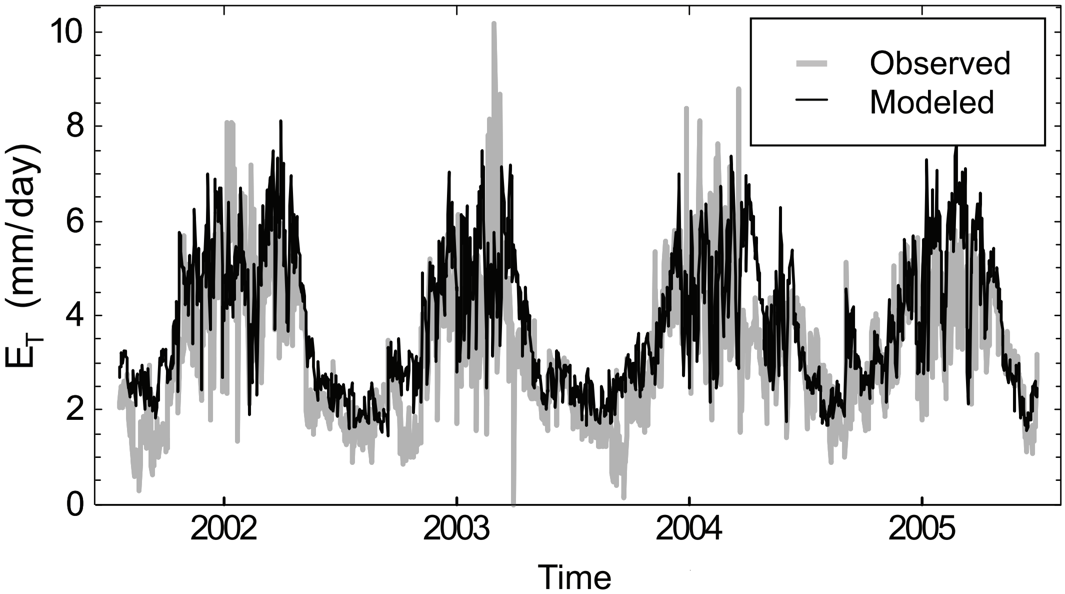


**Fig. 2.** Result of an optimality based modeling framework (from Schymanski et al., 2009b): observed and modeled daily evapotranspiration rates. The model simulates the vegetation that optimizes the net carbon profit given an observed semi-arid climate in Australia.





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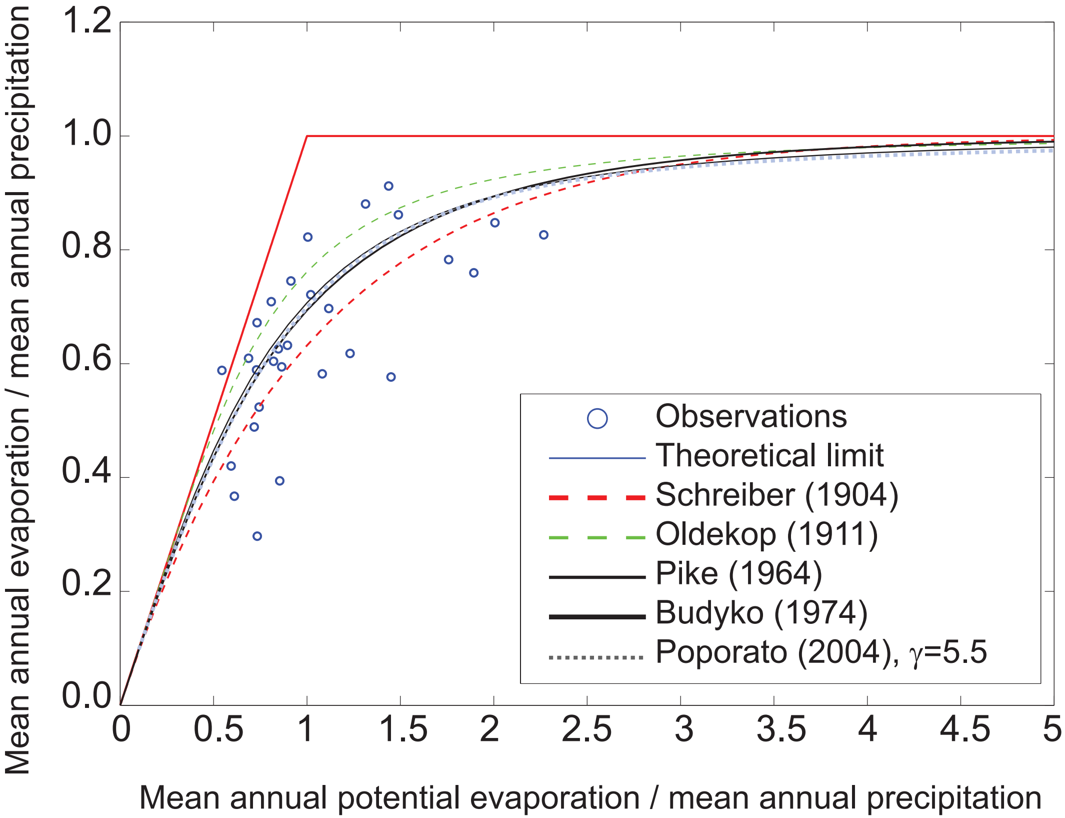


**Fig. 3.** From Gerrits et al. (2009), reproduced with the permission of the authors: different representations of the Budyko curves and some observations. The 1:1 limit expresses the limitation by available energy, and the horizontal limit expresses the limitation by available water.





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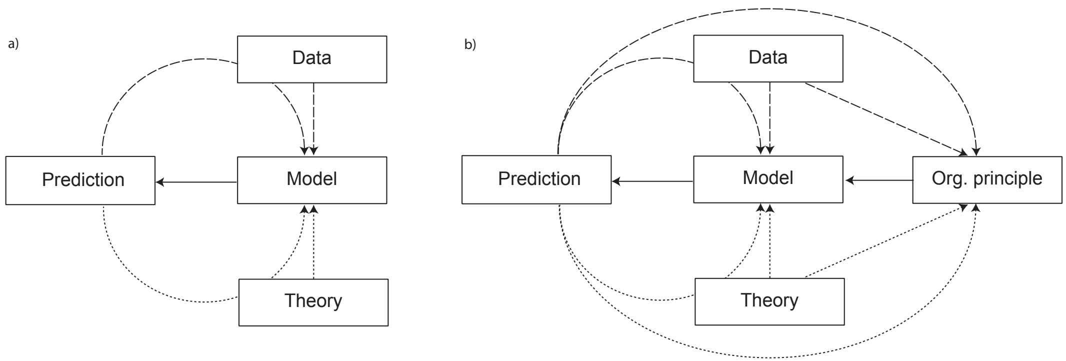


**Fig. 4. (a)** Classical bottom-up (dotted lines) and top-down (dashed lines) model development approach (inspired from Sivapalan, 2005); **(b)** new behavioral framework.



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