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# Catchment Classification and Predictions in Ungauged Basins

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**ABSTRACT:** Current hydrologic predictions are notoriously unreliable if we lack sufficient observations of the hydrologic variable of interest (most often streamflow). In this paper we show how catchment classification can contribute to increase the reliability of ungauged predictions. The basis for a classification framework relying on catchment similarity with respect to physical characteristics, climatic regime and response behavior is discussed. Response behavior can be quantified through signatures (hydrologic indices) that can be regionalized resulting in constraints on the expected behavior of ungauged catchments. Examples of studies utilizing such regional information for the prediction of continuous streamflow are provided. Finally, the discussion is extended to include the concept of catchment services to explicitly address the need for improved support of water resource management. Ultimately such an approach will advance our ability to achieve water security for humans and ecosystems through improved predictions.

## INTRODUCTION

Our ability to predict the hydrologic response behavior of catchments is crucial for operational application such as flood and drought prediction, and it is evidence of our degree of understanding (or lack thereof) of hydrologic systems. In this paper we discuss how a catchment classification system can be used to advance this understanding. A catchment can be defined the area upstream of a point on the river network, commonly delineated using surface topography (Brutsaert, 2005). The catchment forms a landscape element (at various scales) that integrates all aspects of the hydrological cycle within a defined area that can be studied, quantified and acted upon (Wagener *et al.*, 2007). The hydrologic response e.g. streamflow) is a depending on the functions that a specific catchment exerts on the precipitation it collects. Those functions include the partitioning of water into different pathways at the land surface, the storage of water (in fluid or solid form) in different stores with different residence times, and the release of water through different pathways for example as streamflow or evaporation (Figure 1; Wagener *et al.*, 2007). The catchment also transmits water between hillslopes, the riparian zone and the river network; and it acts as a conveyance system for mass and energy (Brutsaert, 2005).

These functional characteristics of catchment are reflected in the observed response behavior, i.e. the response provides a signature of the specific functional behavior of a catchment (Figure 1). Being able to link functional behavior and signatures, and being able to predict the functional behavior based on knowledge of physical catchment characteristics and the regional climatic regime would provide a significant advancement to the current state of hydrologic science. In this paper we discuss how such relationships can be established and they can be used in an uncertainty framework to reduce the uncertainty in predictions in ungauged basins and of predictions of environmental change impacts. We close with a brief discussion of how such a classification framework can be linked with the concept of catchment services to explicitly address water resource management issues.

## HYDROLOGIC SIMILARITY

A classification system groups entities that are similar in some way. In the context of hydrologic science, and with the ultimate objective of providing better hydrologic predictions, our main interest needs to lie in grouping catchments that respond similar when forced with the same precipitation/energy input. Which catchments will provide an equally flashy or damped response, which catchments will provide similar amounts runoff per precipitation input (i.e. have a similar yield), etc. Winter (2001) suggests that, for example, areas having similar land slopes, surficial geology, and climate will result in similar hydrologic flow paths regardless of the geographic location of the site. If this is correct, then we need to look at least at three dimensions of

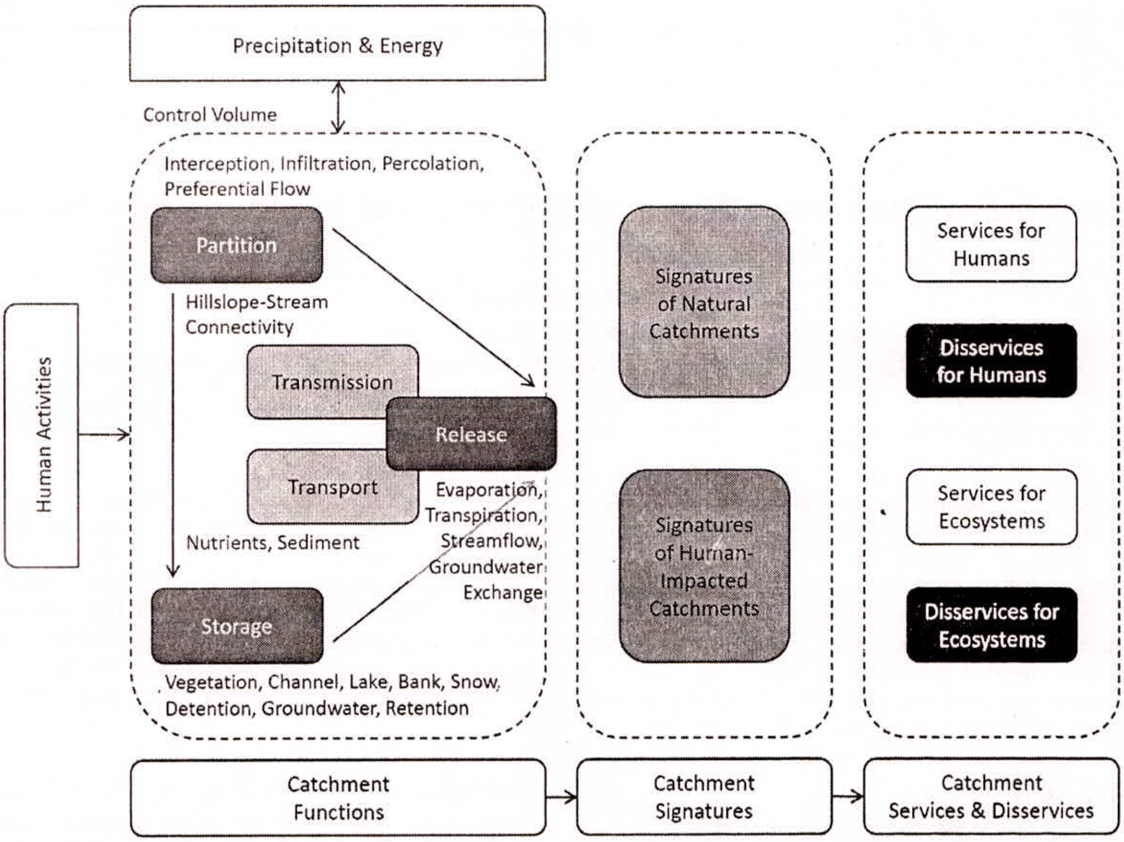

**Fig. 1:** Catchment classification framework based on catchment functional behavior and the concept of catchment services. (Modified from Wagener *et al.*, 2008)

similarity, physical similarity, climatic similarity and hydrologic similarity. Most importantly, we need to understand how these three dimensions map onto each other (Wagener *et al.*, 2008).

Identifying catchment similarity as defined by structural catchment characteristics have a long tradition in hydrology. Characteristics of this type have been proposed in the form of (often dimensionless) numbers, of curves or distributions, and of conceptual and mathematical models. Examples include metrics such as the Strahler order number, the hypsometric curve, etc. Climate is another metric that has a strong impact on hydrologic catchment behavior (Budyko 1974; L'vovich 1979) and even on physical catchment characteristics (Abrahams 1984). The hydro-climatic region in which a catchment is located should play an important role in any classification system due to the amount of energy that is available for evaporation and due to the dominant precipitation regimes (Figure 2). The main differentiating metric between catchments, from a hydrologic point of view, must be the catchment's response behavior and storage characteristics though. Such behavioral characteristics or signatures typically include characteristics of streamflow, but could also extend to evaporation, groundwater dynamics, soil moisture dynamics, snow cover, distributions of residence time and water age, isotopic composition, concentrations of chemicals such as chloride and nitrate (Sivapalan, 2005). The different functions of catchments are reflected in these signatures of hydrologic response behavior. Characteristics of this behavior can be described using signatures, i.e. specific characteristics of the catchment response behavior, which can be linked to any of the functions through hydrological theory (Sivapalan, 2005; Gupta *et al.*, 2008). For example, the term runoff ratio (long term ratio of runoff over precipitation) describes how the catchment releases water through different pathways, evaporative processes versus streamflow.

As we begin to compare and contrast catchments across places (e.g. across diverse climates and geologies), and across processes and functioning, we also recognize likely variations across scales (spatial and temporal). Thus, the general catchment classification scheme we seek to develop will likely require explicit consideration of both spatial and temporal scales. A study by Olden and Poff (2003) demonstrates that daily, monthly, and annual hydrologic indices are not always correlated, suggesting that different or independent information is present at these different temporal scales.

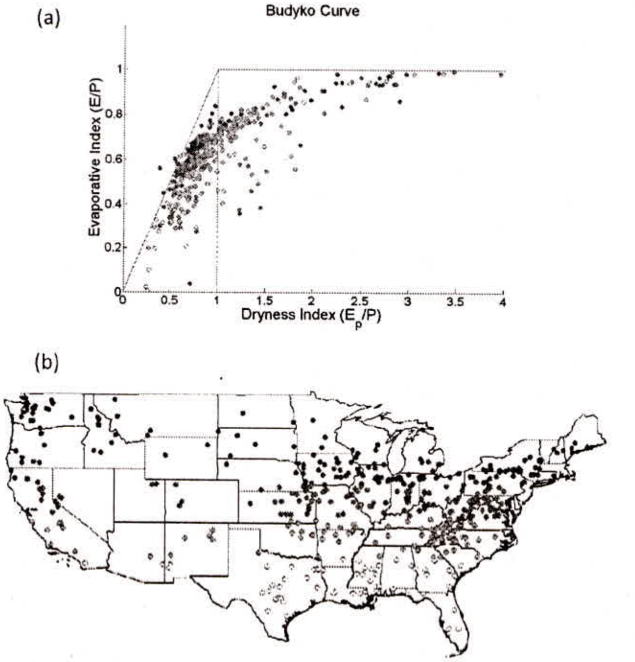

**Fig. 2:** Example of climatic description of catchments using over 400 US catchments. Plot (a) show the Budyko curve plotting the evaporative index, long-term mean annual actual evaporation (E) over long-term mean annual precipitation (P), *versus* the dryness index, long-term mean annual potential evaporation ($E_p$) over P. Plot (b) shows the location of the catchments plotted in the Budyko curve. The gray scale indicates the latitude of the catchment outlet. (Modified from Wagener *et al.*, 2008)

## CATCHMENT CLASSIFICATION

Hydrology does not yet possess a generally agreed upon catchment classification system. Assessing similarity is only a first step towards reaching a hydrologically significant classification framework, since hydrologists have always tried to relate structural features of catchments to their response characteristics (Bras, 1990, p. 589). Such a classification framework should provide a mapping of landscape form and hydro-climatic conditions on catchment function (including partition, storage, and release of water), thus providing insight into causal relationships between these three aspects and to achieve predictive power. It should also explicitly account for variability at multiple temporal and spatial scales (McDonnell and Woods, 2004; Wagener *et al.*, 2007; 2008). This mapping should include the uncertainty in the individual metrics as well as the uncertainty in the mapping itself to acknowledge our lack of knowledge (i.e. gaps in hydrological theory) and our limited capability to observe hydrological processes (Yadav *et al.*, 2007; Zhang *et al.*, 2008). Such a framework would provide an organizing principle, create a common language, guide modeling and measurement efforts, and provide constraints on predictions in ungauged basins, as well as on estimates of environmental change impacts. Catchments are complex environmental systems varying widely in physical characteristics and climatic setting. On the other hand, the catchment is a self organizing system, whose form, drainage network, ground, and channel slopes, channel hydraulic geometries, soils, and vegetation, are all a result of adaptive ecological, geomorphic, and land-forming processes (Sivapalan, 2005). Therefore, while the complexity and the differences between catchments can often be overwhelming, patterns might emerge and connections might be discernible and lead to advancement in hydrologic science through the formulation of hypotheses or relationships that may have general applicability.

Stationarity—the assumption that the variability of natural systems is limited to remain within an unchanging envelope—has become an unsuitable basis for science in a world that is changing at an increasing speed (Milly *et al.* 2008). The reasons for this change in our current and future world are mainly: [1] human changes to land cover and channels (incl. dams) in catchments driven by increasing population size, and subsequent needs for increased agriculture and urbanization, [2] natural and human induced climate change, and [3] natural variability of the climate system. 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.*, 2006a; Oki and Kanae, 2006). Such changes to water pathways, storage and subsequent release (the blue and green water idea of Falkenmark and Rockström, 2004; 2006) 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;

2007; Johnson *et al.*, 2001; Sachs, 2007). The growing imbalances among freshwater supply, its consumption, and human population will only increase the problem (Vörösmarty *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 (Wagener, 2007)? Solving this problem is very similar to solving the predictions in ungauged basins problem, i.e. how can we predict the as yet unobserved response behavior of a catchment before it has been observed?

## ADVANCING PREDICTIONS IN UNGAUGED BASINS

A problem common to all hydrologic models is that they require some degree of parameter calibration to achieve reliable predictions, i.e. a process in which the model parameters are adjusted (manually or automatically) until observed and simulated catchment responses match as closely as possible. This calibration step is by definition not possible if the catchment is ungauged or went through significant changes, e.g. land use. Mainly two approaches have been used to compensate this lack of calibration. In the first approach, model parameters are directly derived from observations of physical catchment characteristics. This approach suffers from differences in scale between model elements and measurements, and from our ability to directly measure the parameters of interest, e.g. subsurface conductivity. An alternative approach is the use of a regionalization strategy in which a typically lumped model is calibrated in many gauged catchments and statistical relationships between model parameters and catchment physical characteristics are derived. This approach suffers from an ill-defined calibration problem and a lack of theory on how catchment-scale model parameters should relate to catchment characteristics. A general experience of hydrologic modelers is that ensemble predictions in ungauged basins derived from a priori feasible model parameter ranges often provide very uncertain streamflow estimates unless local historical observations of streamflow are available (Wagener and Wheater, 2006). Reducing the uncertainty on predictions in ungauged basins is a current focal point of the hydrologic community (Sivapalan *et al.*, 2003). How can we use the concepts similarity and classification for improved predictions in ungauged basins?

An alternative to the derivation of a priori model parameter estimates from physical watershed characteristics lies in the regionalization of streamflow characteristics. Prior studies have found that the correlations between streamflow characteristics and physical watershed characteristics are often significantly higher than between model parameters and watershed characteristics (e.g. Poff *et al.*, 2006a; 2006b; Yadav *et al.*, 2007). Although the correlations between streamflow and watershed characteristics do not directly provide predictions of the continuous streamflow hydrograph, regionalized flow characteristics provide dynamic aspects of the watershed system that can be used to constrain hydrologic model predictions. Yadav *et al.* (2007) revised the regionalization of flow characteristics by including estimates of uncertainty in the regression equations. Uncertainty ranges, in addition to the expected values of flow characteristics, are valuable sources of information for constraining a model and thus for providing ensemble predictions at ungauged locations. Yadav *et al.* (2007) showed in a pilot study using 30 UK catchments shows how this regionalized information can be used to constrain ensemble predictions of any model at ungauged sites. Dominant controlling characteristics were found to be climate (wetness index), topography (slope), and hydrogeology. Main streamflow indices were high pulse count, runoff ratio, and the slope of the flow duration curve. Creating streamflow ensembles from a priori (unconstrained) feasible parameter sets produced very uncertain predictions at ungauged locations. This uncertainty reduced significantly when ensemble members that conflicted with the regionalized flow characteristics (i.e. the constraints) were rejected.

The work of Yadav *et al.* (2008) provides an avenue to assimilate regional information to reduce the uncertainty in continuous predictions of streamflow at ungauged locations. It could equally be used to assess the impact of change (Wagener, 2007). However, there have been decades of research into developing powerful global optimization algorithms (Wagener and Gupta, 2005) that, as yet, are unused in ungauged circumstances. Zhang *et al.* (2008) recently suggested a solution to this problem by introducing a novel multiobjective framework for identifying behavioral parameter ensembles for ungauged basins using suites of regionalized hydrologic indices, i.e. constraints. The new formulation enables the use of multiobjective optimization algorithms for the identification of model ensembles for predictions in ungauged basins for the first time. Application of the new formulation to the 30 watersheds of Yadav *et al.* (2007), and a comparison of the results with the previously used Monte Carlo approach demonstrate that the new formulation will significantly advance our ability to reduce the uncertainty of predictions in ungauged basins (Figure 3). The high efficiency and robustness of the ε-NSGAII (The Multiobjective Genetic Algorithm used in their study) in finding behavioral parameter sets indicates that (1) more complex (incl. distributed) hydrologic model decision spaces can be searched using the multiobjective Prediction in Ungauged Basins (PUB) framework presented in this study, and (2) an increasing number of hydrologic indices can be tested for constraining ensemble predictions for ungauged basins. Zhang *et al.* (2008) demonstrate that PUB can be viewed as a new class of multiobjective search problems. Reformulating the PUB problem as a multiobjective search for behavioral model parameter sets, generalizes our ability to test a wide range and number of hydrologic indices to maximize our use of the information available in streamflow datasets. The PUB problem formulation contributed in their study can be easily adapted to solve larger, more computationally demanding model identification problems. This will have particular value for future studies seeking to develop high fidelity, probabilistic scenarios for environmental change under uncertainty (Wagener, 2007).

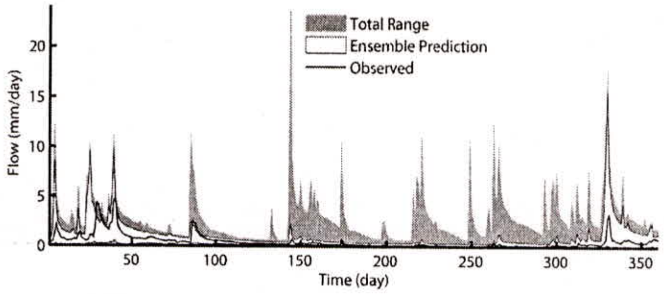

**Fig. 3:** Example of a daily streamflow prediction in an ungauged UK basin as unconstrained ensemble (grey) and constrained ensemble (white). The unconstrained ensemble was produced through randomly sampling from a priori feasible parameter ranges of a 5 parameter lumped hydrologic model. The ensemble was constrained by three regionalized streamflow indices describing water yield, baseflow contribution and flashiness of a catchment. (Modified from Zhang *et al.*, 2008)

## CONCLUSIONS AND OUTLOOK

In conclusion, it is important to look towards how this discussion on catchment classification can ultimately advance our ability to better use models in support of water management for water security of humans and ecosystems from lack or excess of water. While hydrologic signatures (indices) describe hydrologically relevant characteristics of the catchment response, it is crucial to include the implication of the values of different signatures for humans and ecosystems. This inclusion creates a classification framework which explicitly defines the societal relevance of catchment behavior and which is directly significant for water resource management (Figure 1). Here we distinguish positive and negative implications of catchment functions (as reflected by the signatures) for humans and ecosystems. Benefits received by humans supplied by resources and processes of natural ecosystems have become known as ecosystem services (e.g. Daily, 1997). Here, we are concerned with the positive impacts or benefits received by nature (ecosystems) and humans from resources and processes supplied by catchments, and will therefore refer to these as *catchment services*. The classification discussed, based on physical characteristics, climatic characteristics and signatures, can provide significant advances to our ability to predict the continuous streamflow response of ungauged basins. These ensembles predictions subsequently enable us to extract any (streamflow related) indicator that relates to catchment services (or disservices) provided to humans or ecosystems (Wagener *et al.*, 2008).

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