Hydrologic Similarity and the Search for a Catchment Classification Framework

Thorsten Wagener
Civil & Environmental Engineering, Pennsylvania State University
Currently Humboldt Fellow & Visiting Professor @ the Institute of Hydrology, University of Freiburg, Germany

This work was done in collaboration with a wide range of graduate students and colleagues!

http://water.engr.psu.edu/wagener/
There is an increasing need for hydrologic predictions in support of a wide range of water resources services. These predictions need to be available everywhere and represent past, current and potential future conditions, incl. uncertainty.

... To achieve this, we need to ensure our models work for the right reasons, and use available data optimally.

This Talk focuses on Hydrologic Similarity and its Relevance...

Hydrologic Similarity

Catchment Classification

PUB and Long-term Projections

Diagnostic Model Evaluation
HYDROLOGIC SIMILARITY

[http://mapmaker.rutgers.edu/355/Chernoff_face.gif]
Why do we care about hydrologic similarity?

• Because it allows for the transfer of information/knowledge (incl. predictions).
• Because it enables the generalization of results (Dooge’s search for hydrologic laws?).
• Because it provides benchmarks and baselines.
What should the metrics be that define similarity or dissimilarity between catchments in a hydrologically relevant manner?

1. Physical, i.e. catchments similar in form.
2. Climatic, i.e. catchments located in similar climate.
3. Streamflow, e.g. ecological indices.
4. Behavioral, i.e. catchments similar in function.
5. Geographical, i.e. catchment located in close proximity.

I will not consider proximity here since considering proximity alone is not scientific, since there has to be another underlying cause of the similarity, i.e. form or climate.
Neither form, function or climate alone will be sufficient descriptors, but it is in understanding the mapping between them where the science lies.

Previous attempts for such mappings include conceptual models such as Dunne’s dominant hillslope processes, Buttle’s T3 template, Winter’s hydrologic landscapes, metrics by Milly, R. Woods, etc. However!

[Wagener et al., 2007, Geography Compass]
Key points regarding hydrologic similarity

• The concept of hydrologic similarity is fundamental to hydrologic science
• There isn’t a single unique approach to define such similarity – we need to look at this issue in different ways, but also take the time to compare the results
• Understanding comes from the mapping between form, function and climate
RELEVANCE OF H.S. FOR CATCHMENT CLASSIFICATION
Hydrology does not yet possess a generally accepted catchment classification system

..., but what form should our classification framework take?
A catchment classification framework could and should (!) ...

1. give names to things, i.e. the main classification step
2. enable transfer of information, i.e. regionalization of information
3. enable development of generalizations, i.e. to develop new theory
4. provide a first order environmental change impact assessment, i.e. climate and land use change

[Grigg, 1965 and 1967; McDonnell and Woods, 2004, HP; Wagener et al., 2007, Geography Compass]
One strategy is to place classification in a function/signature framework.

[Black, 1997; Wagener et al., 2007, Geography Compass]
Hydrologic signatures are indices that provide insight into catchment functions.

What signatures can we use to capture key differences in hydrologic function of catchments?

[Yadav et al., 2007, AWR]
We start by assuming that 6 key signatures capture the main catchment functions

1. Runoff Ratio describes how water is released from the catchment (ET vs Q)
2. Flow Duration Curves describe how strongly the rainfall signal is filtered by the catchment
3. Baseflow Index describes the ‘flow path’ water is taking through the catchment
4. Streamflow Elasticity describes how sensitive streamflow is to precipitation change
5. Ratio of Snow Days describes the importance of snow storage
6. Rising Limb Density describes the flashiness of the catchment response

[Sawicz et al., In Review, WRR]
The 6 signatures show different spatial patterns.

How do these signatures group hydrologically similar catchments? We use a Bayesian clustering algorithm to test this.

[Sawicz et al., In Review, WRR; Achcar et al., 2009, Nucleic Acids Research]
Signatures vary within and across classes, but show the strong impact of climate and geology.

[Sawicz et al., In Review, WRR]
Analyzing heuristics of the clustering results, most catchments show a clear classification, but some seem unique.

[Sawicz et al., In Review, WRR]
The result is a rainbow of characteristics, but also some homogeneous groups

The outliers (low probability of unique classification) are distributed across most classes

[Sawicz et al., In Review, WRR]
The resulting classification shows a mix of spatial coherence and heterogeneity

[Sawicz et al., In Review, WRR]
Key points regarding classification

• Classification can be viewed as one way to take stock regarding our understanding of hydrologic similarity (and its controls) across the vast heterogeneity of catchments
• To understand similarity within the ‘world population of catchments’ requires community activities, e.g. the creation of large heterogeneous datasets with data beyond Q-P-T
• A combination of empirical and model-based approaches will be necessary to achieve generalization of results
RELEVANCE OF H.S. FOR DIAGNOSTIC MODEL EVALUATION
Most (all?) models require some degree of calibration to observed data, traditionally we defined some statistical measure to evaluate performance.

\[ RMSE = \sqrt{\frac{1}{m} \sum_{i=1}^{m} (Q_{s,t} - Q_{o,t})^2} \]

[Gupta, Wagener, Liu 2008 Hydrological Processes]
However, evaluation of hydrological models has at least 3 dimensions

How can we test the hydrologic similarity between catchment and model, i.e. realism?
[1] We can look at the performance in reproducing signatures, e.g. FDC

[2] We can use sensitivity analysis to quantify how the model produces these signatures (= realism)

We found the sensitivity analysis approach by Sobol effective and it is the basis of the results shown here [Tang et al., 2007, HESS]

[Yilmaz et al., 2008, WRR]
Comparing signatures and understanding how the model simulates them provides diagnostic information.

[Source: Gupta, Wagener, Liu 2008 *Hydrological Processes*]
Case study: A popular lumped watershed model, i.e. the Sacramento model
We utilize both statistical and ‘hydrological’ (signature) objective functions
We find significant variability in parameter sensitivity across the study region. Patterns are correlated to hydroclimate, R up to 0.96. Impervious area parameters important for peaks. Lower zone impacts peaks through percolation. Similar lower zone behavior for RMSE and TRMSE. Importance of parameters that control ET losses. Large differences between driest and wettest conditions. [van Werkhoven et al. 2008 WRR]
The strength of the sensitivity is most strongly related to a climatic gradient allowing to test the realism of the model.

Thus parameter sensitivity varies in space, but also potentially in time ➔ climate change impacts!

[Tang et al., 2007, WRR; van Werkhoven et al. 2008 WRR; 2008, GRL]
Key points regarding diagnostic evaluation

• It is crucial to evaluate our models in a hydrologically meaningful way to test whether they work for the right reasons, i.e. hydrologic similarity

• We need to test model behavior across many watersheds to understand how similar or dissimilar models reflect the behavior of different systems

• Such understanding is crucial for advancing model development, for effective model calibration, and for estimating the impacts of environmental change
How can we assess models without local historical observations of streamflow?

RELEVANCE OF H.S. FOR PUB AND FOR LONG-TERM PROJECTIONS
Necessary tools for prediction/projection:

A model & a parameter set (or multiple of each)

The problem: We need historical observations of streamflow (or other response variables) at the prediction location to calibrate the model! Without such data, uncertainty in predictions is often high and robustness is low.
Our ability to make useful predictions depends on how much we can reduce this uncertainty.

\[
\text{Posterior} \propto \text{Prior} \times \text{Likelihood}
\]

Ungauged or change situation!

So what can we do in the case of ungauged basins or in the case of predicting environmental change impacts?

[Wagener, 2007, HP; Wagener and Montanari, In Review, WRR]
Traditionally we focused on deriving priors on the parameters through similarity concepts.

Problems:
- Model Structural Error?
- Calibration Problem?
- Catchment Characteristics?

[Wagener and Wheater, 2006, J. Hydrology]
Regionalizing signatures provides an additional 'likelihood' for modeling ungauged locations.

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[Yadav et al., 2007, *AWR*; Zhang et al. 2008, *WRR*]
We can sample from the prior uncertainty in the parameters and assimilate the likelihood (formally or as constraints/limits of acceptability). The result can be a significant further reduction in predictive uncertainty in ungauged basins!

[Yadav et al., 2007, AWR; Zhang et al. 2008, WRR]
Another important question next to PUB, is PUT = Predictions in Ungauged Times!

Several recent studies show a strong climate dependence of calibrated parameters.

We can use the same idea of signature regionalization to address this issue.

E.g. climate change impact studies or retrospective analysis.

[Wagener, 2007, HP; Wagener et al., 2010, WRR]
We can regionalize climate controlled signatures (e.g. runoff ratio) and calibrate the model in a particular watershed to the climate that is similar to what long-term projections suggest

One important current question is: How sensitive are watersheds to a changing climate (P & T), i.e. what is their streamflow (Q) elasticity?
The resulting elasticity estimates show more change in $Q$ than with a historically calibrated model.

For example, estimates are worse for drier and warmer climates, hence for many less developed parts of the world!

[Singh et al., In Preparation]
Key points regarding PUB & PUT

• How to estimate parameters for our models at ungauged locations and under changing conditions (climate or land cover) remains an issue
• Signature regionalization can provide additional information that can be assimilated into hydrological models as constraints or likelihoods
• Trading-space-for-time enables the consideration of the impact of changing conditions on the parameterization of models
Progress on the issue of hydrologic similarity requires analyses and meta-analyses of multi-method/multi-watershed studies beyond individual investigators.

Hopefully in a way that is more civilized than with this rowdy bunch!
To conclude …

- Understanding hydrologic similarity is important for advancing hydrologic science (actually it is a major foundation!)
- It is the relationship (mapping) between form, function and climate that we have to understand across spatial and temporal scales
- It is likely that considerable uncertainties and outliers will remain, hence the need to include uncertainty in both characterization and mapping
- The result can provide an assessment of our current state of knowledge, a first-order model for ungauged basins and for change impacts, and can provide constraints for modeling (predictions and diagnostics)

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