Data analysis and model building for understanding catchment processes: the case study of the Thur catchment

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Abstract

The development of semi-distributed hydrological models that reflect the dominant processes controlling streamflow spatial variability is a challenging task. In small, well-instrumented headwater catchments the model can be built taking advantage of knowledge derived from extensive fieldwork activities; that is, however, not possible in much larger catchments where, usually, these models are actually needed. To address this problem, we propose a new methodology where we analyze the correlations between hydrological signatures, catchments characteristics, and climatic indices to get insights about the hydrological functioning of the catchment and to guide the decisions involved in the development of a semi-distributed model. The methodology is tested in the Thur catchment (Switzerland, 1702 km2); in a first stage we show how to identify catchment characteristics and climatic indices that control streamflow variability; in a second stage, we use these findings to develop a set of model experiments aimed at determining an appropriate model representation for the catchment. Results show that only models that account for the influencing factors indicated by the correlation analysis are able to represent correctly the observed streamflow signatures, confirming our understanding of the processes happening in the catchment.

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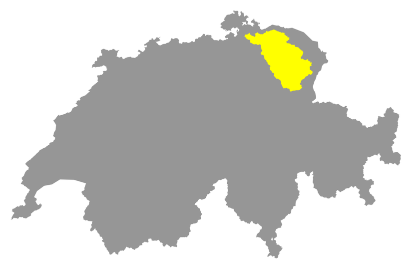
Objectives

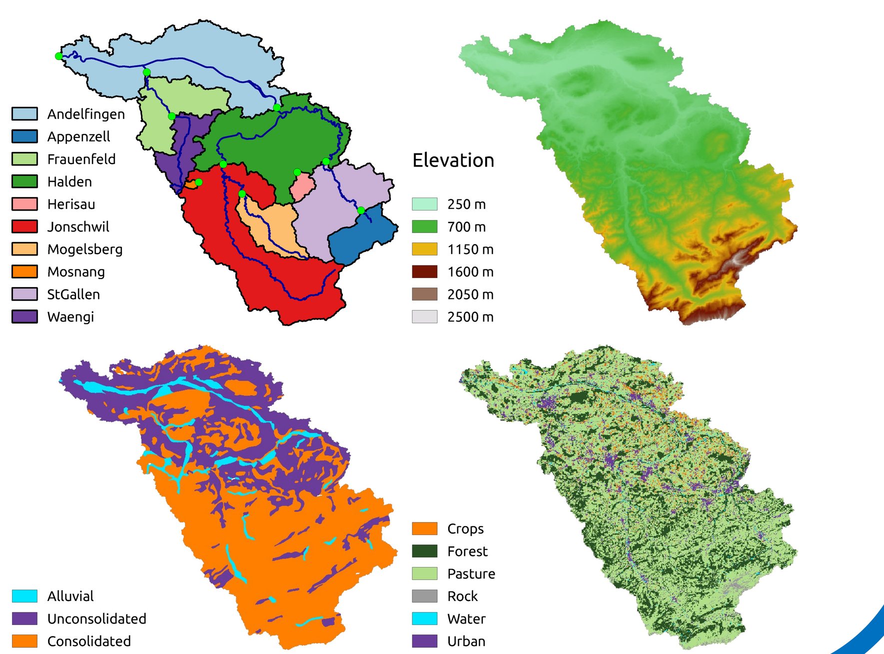
- Understanding causes of streamflow spatial variability
  - Influence of meteorological input
  - Influence of catchment characteristics
- Build a hydrological model that is able to represent streamflow spatial variability

Study area

The Thur is an alpine and pre-alpine catchment in the north-east of Switzerland and it is characterized by a large spatial variability in terms of:

- Streamflow characteristics
- Climatic conditions
- Physical characteristics





Indices

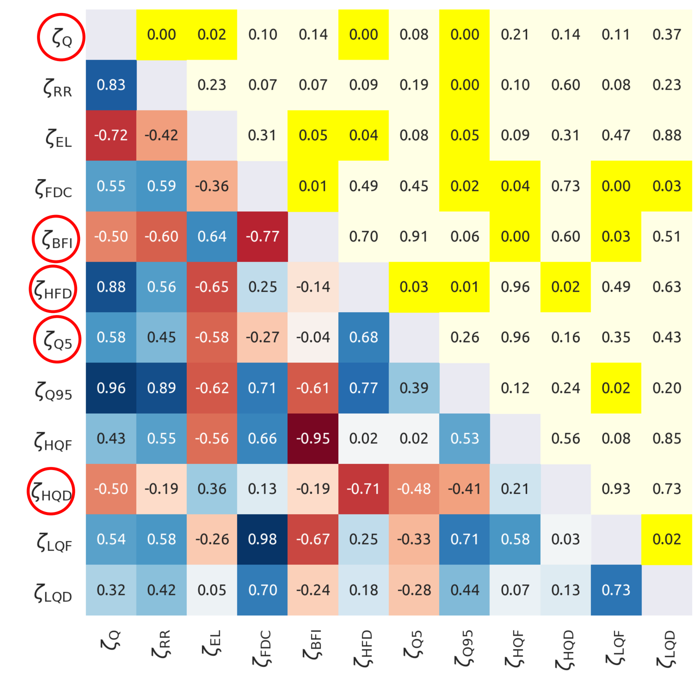
Streamflow signatures			
ζ_{Q}	Average daily streamflow	ζ_{Q5}	5th streamflow percentile
ζ_{RR}	Runoff ratio	ζ_{Q95}	95th streamflow percentile
ζ_{EL}	Streamflow elasticity	ζ_{HQF}	Frequency of high-flow events
ζ_{FDC}	Slope of the flow duration curve	ζ_{HQD}	Duration of high-flow events
ζ_{BFI}	Baseflow index	ζ_{LQF}	Frequency of low-flow events
ζ_{HDF}	Mean half streamflow date	ζ_{LQD}	Duration of low-flow events
Climatic indices			
ψ_{P}	Average daily precipitation	ψ_{HPD}	Duration of high-precipitation events
ψ_{PET}	Average daily PET	ψ_{HDS}	Season with most high-precipitation events
ψ_{AI}	Aridity index	ψ_{LPF}	Frequency of low-precipitation events
ψ_{FS}	Fraction of snow	ψ_{LPD}	Duration of low-precipitation events
ψ_{HPF}	Frequency of high-precipitation events	ψ_{LPS}	Season with most low-precipitation events
Catchments characteristics			
ξ_{A}	Area	ξ_{SD}	Fraction with deep soil
ξ_{TE}	Elevation	ξ_{LF}	Fraction with forest land use
ξ_{TSm}	Slope	ξ_{LC}	Fraction with crops land use
ξ_{TSs}	Fraction of seep areas	ξ_{LU}	Fraction with urban land use
ξ_{TAs}	Fraction facing south	ξ_{LP}	Fraction with pasture land use
ξ_{TAn}	Fraction facing north	ξ_{GA}	Fraction with alluvial geology
ξ_{TAew}	Fraction facing east or west	ξ_{GC}	Fraction with consolidated geology
ξ_{SM}	Soil depth	ξ_{GU}	Fraction with unconsolidated geology

Indices selection

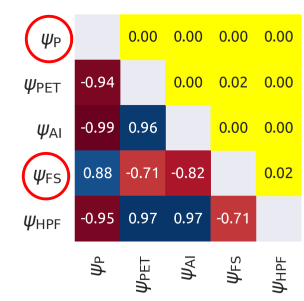
Streamflow signatures, climate indices, and catchment characteristics chosen may be redundant; the list has been reduced according to the following criteria:

- since the interest is in discovering causes of streamflow variability, indices that did not show sufficient variability (coefficient of variation < 5%) have been discarded;
- catchment characteristics that cover a limited part of the catchment (area < 5%) have been discarded;
- among the remaining indices, only relatively independent indices have been kept. Dependency is assessed through Spearman's rank correlation. Results are showed below.

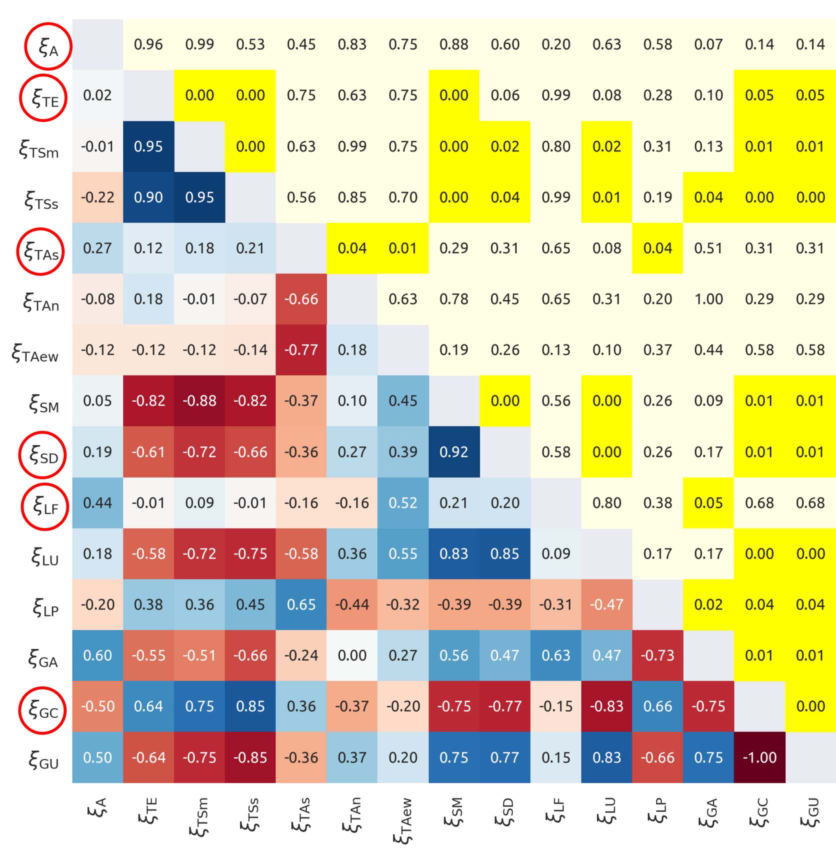
Streamflow signatures



Climatic indices

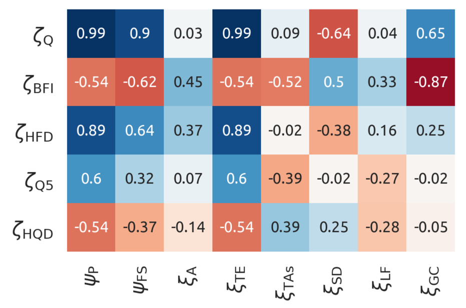


Catchment characteristics



Correlations

Correlations between streamflow signatures and climatic indices and catchment characteristics have been investigated for understanding controls on streamflow spatial variability.



Model building

The results of the correlation analysis have been interpreted and transformed in hypotheses on the functioning of the catchments. These hypotheses have been tested through controlled model comparison.

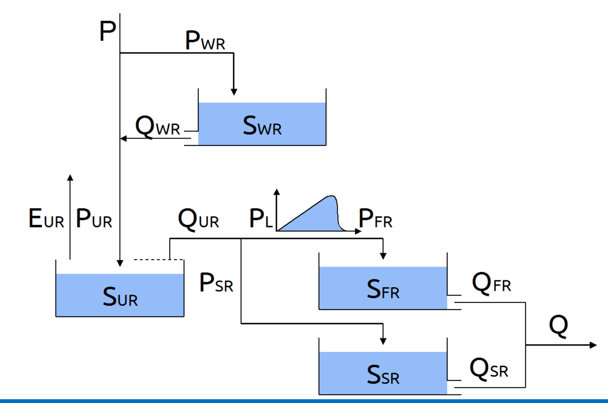
Precipitation is the first driver of differences in the water balance	**H0** →	The model should distribute the precipitation among the catchments
Snow processes control seasonality	**H1** →	The model should represent snow processes
Geology controls the partitioning between quick flow and baseflow	**H2** →	The model should include geological properties into its spatial representation
Other catchment characteristics do not correlate strongly with streamflow signatures	**H3** →	A model that includes other catchment characteristics should not have better performance

Model experiments

To verify the hypotheses H0 to H3, 4 model configurations have been considered:

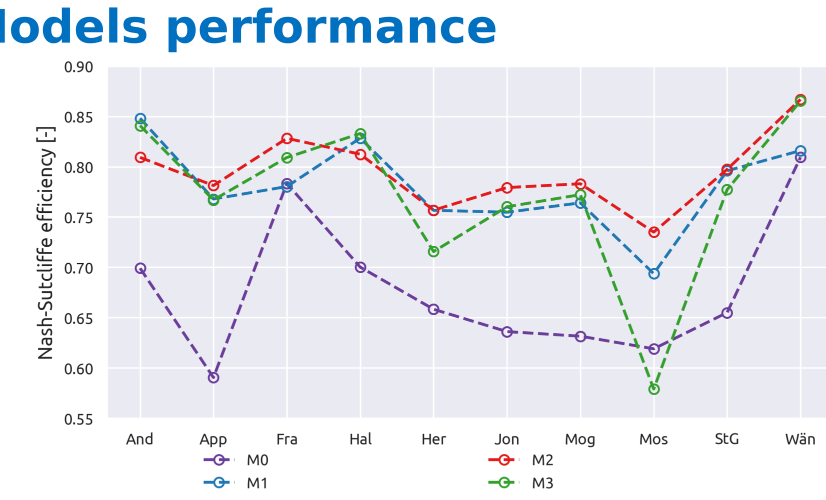
- **M0**: model with distributed inputs, single HRU, and without the representation of snow processes;
- **M1**: M0 with the representation of snow processes;
- **M2**: M1 with 2 different HRUs defined based on the geology;
- **M3**: M1 with 2 different HRUs defined based on the land use; this model, while being as complex as M2, should not improve the results of M1 since the spatial distribution is not based on catchment properties that show correlation with streamflow signatures.

All the model share the same structure for the representation of the HRUs. Note that M0 does not include the snow reservoir WR.

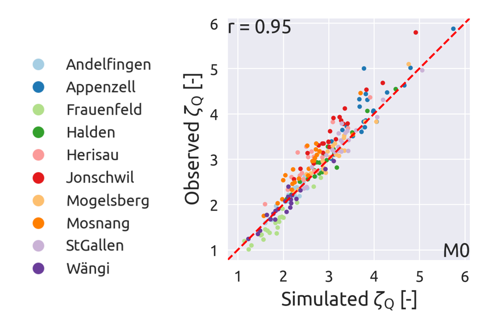


Results

Models performance

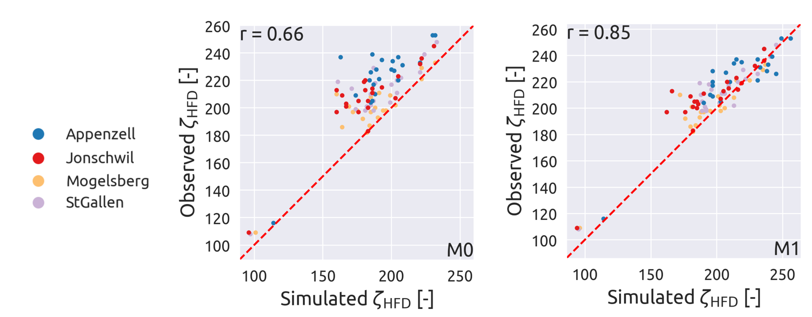


Mean streamflow variability



The simplest model (single HRU, without snow component) is already able to capture the mean streamflow variability, simply distributing the precipitation.

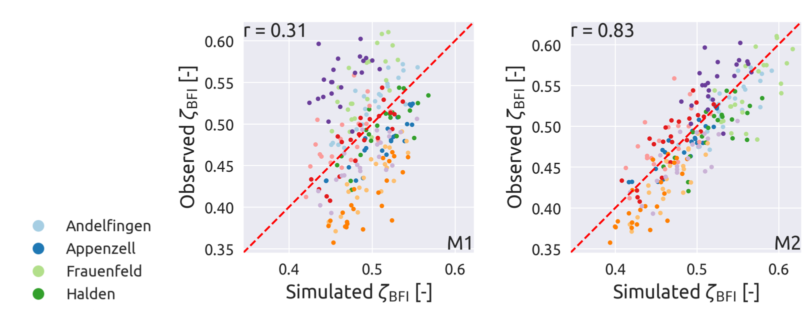
Streamflow seasonality variability

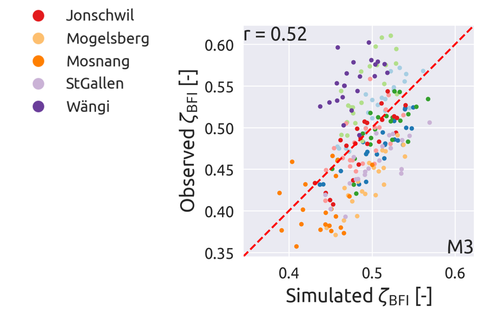


The simplest model (M0) does not include a snow component and, therefore, if fails in representing the differences in seasonality among the catchments.

Adding only the snow component (M1) allows us to achieve a good representation of the differences in seasonality, without the need to increase the complexity of the model.

Baseflow index variability





Out of all the model configurations considered, only M2 is able to correctly represent the baseflow index.

M2 has 2 HRUs based on geology, that is the only catchment characteristics that correlates with the baseflow index. A simpler model (M1) or a model with identical complexity but based on other catchment characteristics (M3) is not able to represent the spatial variability of the baseflow index.

Conclusions

We have presented a **methodology** for the construction of a semi-distributed hydrological model where model **hypotheses** are informed by preliminary analysis on determining the dominant **controls** on streamflow spatial variability.

Results show that:

- there is large **variability** between the subcatchments of the Thur in terms of streamflow signatures, climatic indices, and catchment characteristics;
- main controls of streamflow spatial variability can be identified using **expert judgement** aided by correlation analysis;
- **signatures** analysis can be used to formulate hypotheses about the functioning of the catchment;
- **model experiments** can be constructed to confirm the hypotheses formulated; in particular:
  - M0 shows that distributing the precipitation among the subcatchments is sufficient to represent the mean streamflow variability;
  - M1 shows that the difference in seasonality among the subcatchments is mainly due to snow dynamics: just adding a snow component in the model is enough to achieve great performance regarding this signature.
  - M2 shows that only a model that incorporates the geology is able to represent the variability of the baseflow index, as suggested by the correlation analysis.
  - M3, while being more complex than M1, does not have better results since its increased complexity is not motivated by processes representation.

SuperflexPy

SuperflexPy is a new open source framework for building lumped and semi-distributed conceptual hydrological models. Based on our previous experience with Superflex, the new SuperflexPy improves it in several aspects:

- it is easier to use and to extend;
- it enables to construct spatially distributed models;
- it is written in pure Python but it maintains great performances
- it is completely open for post-run inspection

https://superflexpy.readthedocs.io

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