Assessment of Suitability of Hydrological Models for Climate Change Impact Studies

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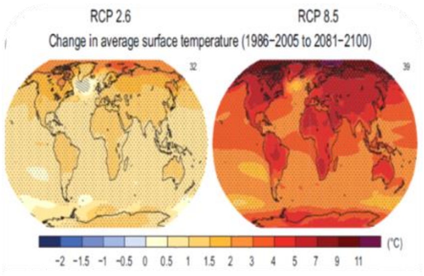
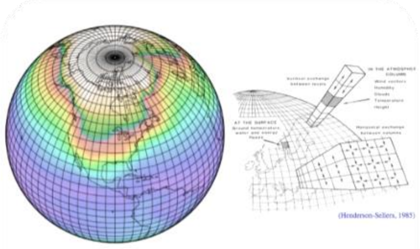
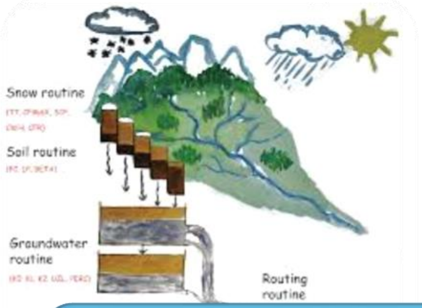
Assessment of Climate Change Impacts on Water Resources



Climate Change Scenario
- RCP



Climate Projections
- GCM
- Down-scaling
- Bias-adjustment

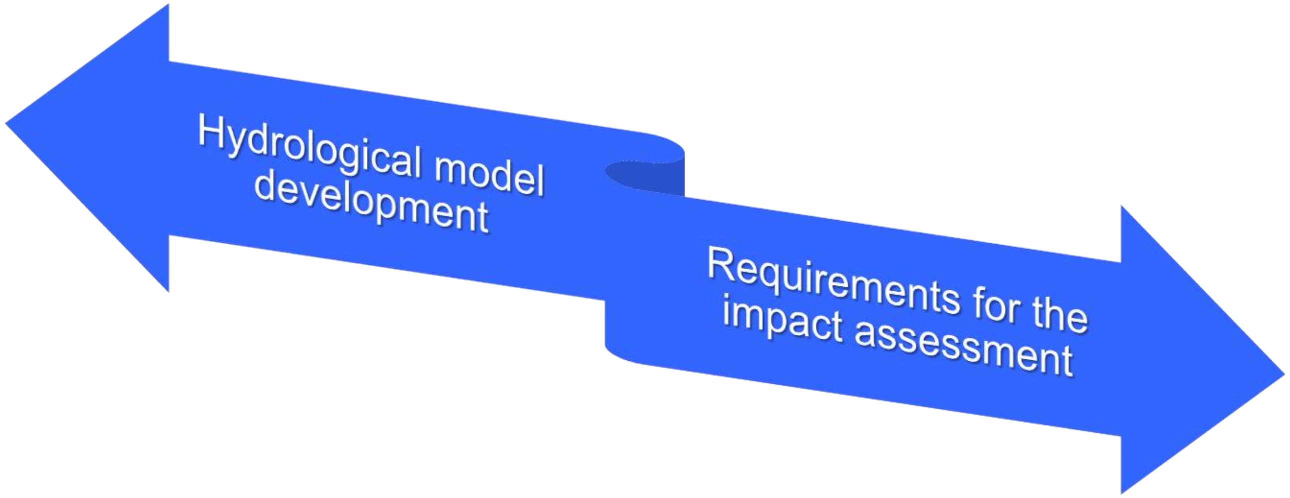


Hydrological Projections
- Simulations in the baseline and future periods

Climate change impact assessment

Hydrological Models and Climate Change Impact Studies

- Hydrological models: calibrated to reproduce *entire* flow series
- Climate model outputs: bias-adjusted to reproduce *distributions* of climate variables
  (e.g., precipitation, temperature)
- Climate change impact studies: estimation of changes in *hydrologic signatures*
  (mean flows, flow seasonality, flood flows, minimum flows of certain duration)



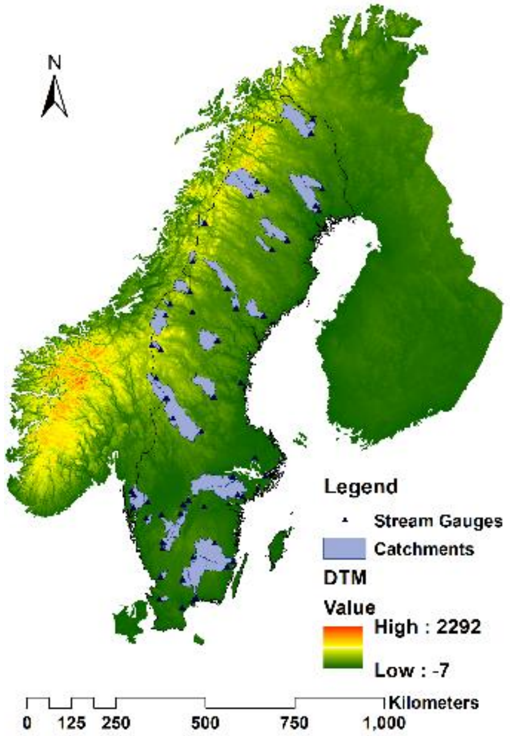
Research Questions

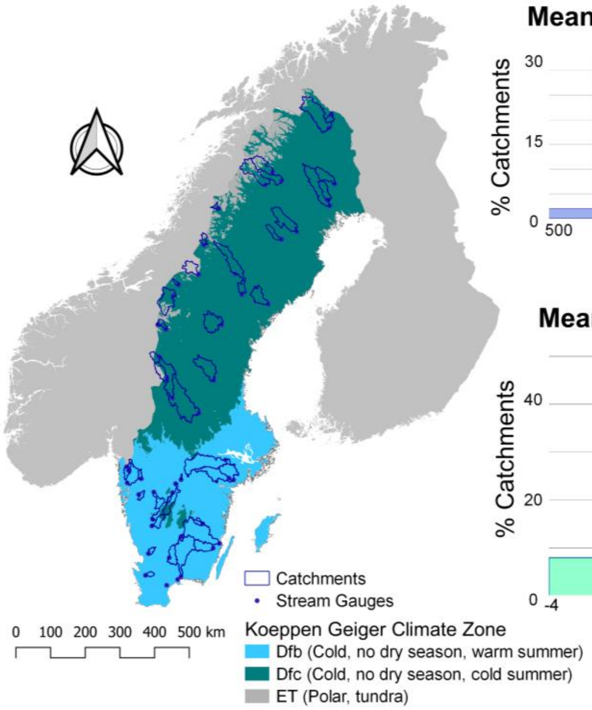
1. Can hydrological models accurately reproduce distributions and trends in series of hydrologic signatures?

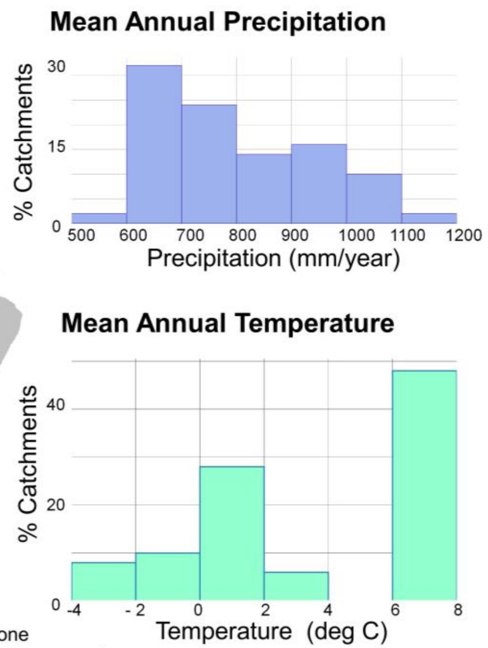
2. Are performance indicators used in hydrological modelling informative about these aspects of model performance?

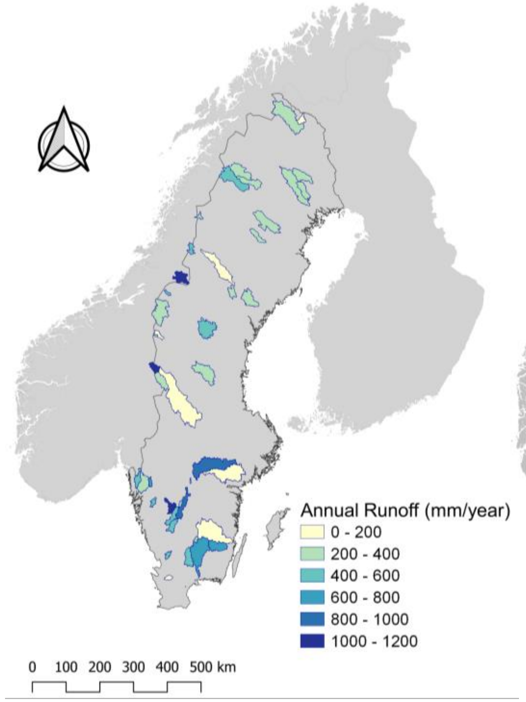
Catchments and Data

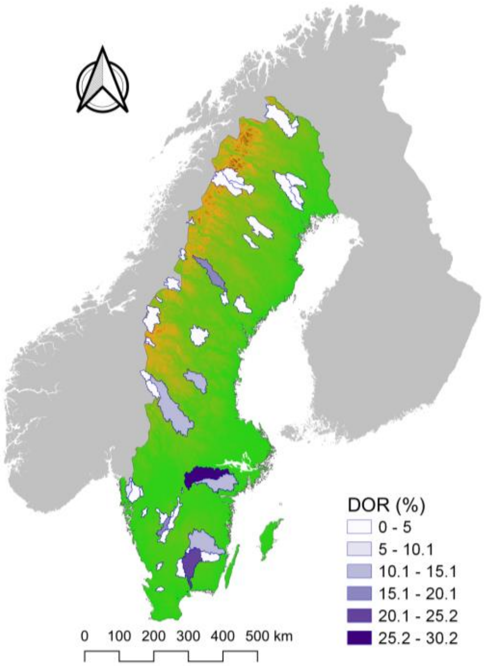
- Analyses are conducted in 50 unimpaired catchments in Sweden
- Daily data over period 1961-2020
  - Precipitation and temperature series: from gridded datasets
  - PET – computed with the Hamon method
  - Daily flows for model calibration and evaluation









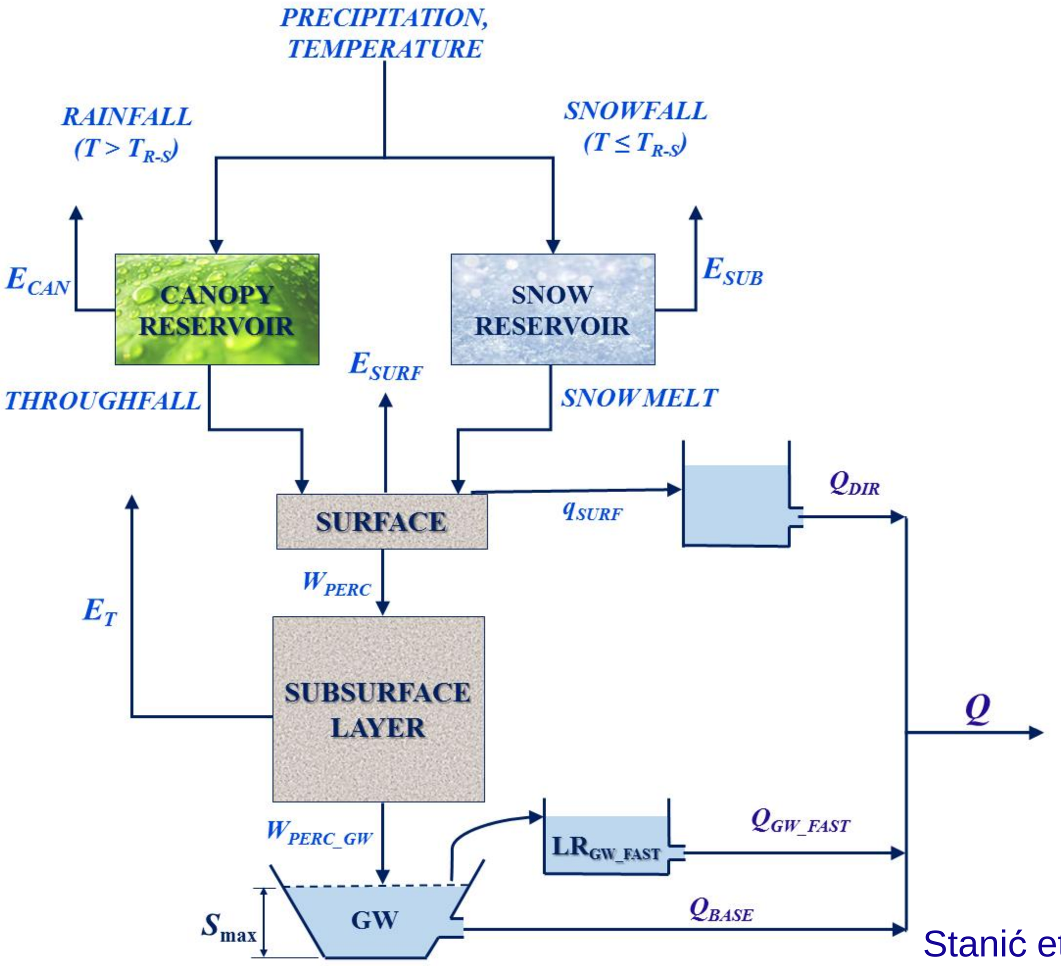


Hydrological Model Implementation in 50 Catchments

- Spatially-lumped version of the 3DNet-Catch hydrological model
- The 3DNet-Catch hydrological model is calibrated in every catchment individually
  - Calibration is performed to achieve balance between runoff volume, high- and low-flows

$$OF = 0.8KGE + 0.2KGE_{1/\sqrt{Q}}$$

  - "Calibration": selection of the set that yields the highest value of *OF* out of 75,000 sampled ones
  - Simulations over water years:
    - Calibration period: 1962-1991
    - Evaluation period: 1991-2020
    - Full record period: 1962-2020



Stanić et al. (2018)

Performance Indicators

- Various indicators are computed with the selected sets in each catchment
    - Runoff volume and dynamics
    - High- and low-flows

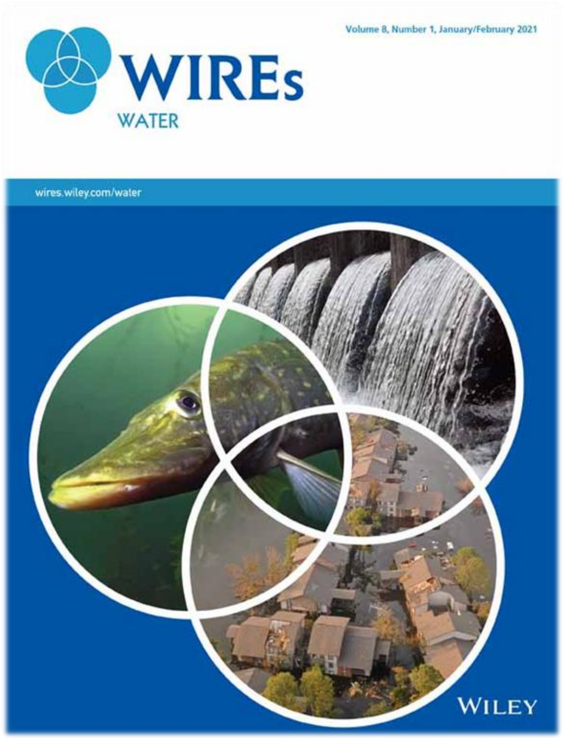
- Higher indicator value – better performance

Notation	Description of Performance Indicator and References	Equation
KGE	Kling-Gupta efficiency coefficient is computed from: – daily flows, *KGE* (Gupta *et al.*, 2009) – reciprocal of root-transformed daily flows, $KGE_{1/\sqrt{Q}}$, to put more emphasis on low flows (Santos, Thirel and Perrin, 2018) – daily flows in a representative year, KGE_{wy}, obtained by averaging daily flows on a specific calendar day over the entire simulation period (Schaefli *et al.*, 2014)	$KGE = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2}$ $r = \frac{\sum(Q_{obs,i} - \bar{Q}_{obs})(Q_{sim,i} - \bar{Q}_{sim})}{\sqrt{\sum(Q_{obs,i} - \bar{Q}_{obs})^2 \sum(Q_{sim,i} - \bar{Q}_{sim})^2}}$ $\alpha = \frac{\hat{S}_{Q_{sim}}}{\hat{S}_{Q_{obs}}}$ $\beta = \frac{\bar{Q}_{sim}}{\bar{Q}_{obs}}$
$NPKGE$	Non-parametric formulation of *KGE* indicator (Pool, Vis and Seibert, 2018). It is computed as *KGE*, with Spearman instead of Pearson correlation coefficient, and with the ratio of standard deviations estimated from FDCs.	$NPKGE = 1 - \sqrt{(r_{Spearman} - 1)^2 + (\alpha_{NP} - 1)^2 + (\beta - 1)^2}$ $\alpha_{NP} = 1 - \frac{1}{2}\sum_{i=1}^{N}\left\lvert \frac{FDC_{sim,i}}{N\bar{Q}_{sim}} - \frac{FDC_{obs,i}}{N\bar{Q}_{obs}} \right\rvert$
NSE	Nash-Sutcliffe efficiency coefficients (Nash and Sutcliffe, 1970) are computed from daily (*NSE*) and log-transformed daily flows (NSE_{logQ}).	$NSE = \frac{\sum_{i=1}^{N}(Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{N}(Q_{obs,i} - \bar{Q}_{obs})^2}$
LME	Liu-Mean Efficiency represents a modification of *KGE* computed from daily flows (Liu, 2020)	$LME = 1 - \sqrt{\left[(k_1 - 1)^2 + (\beta - 1)^2\right]}$ $k_1 = r\frac{\hat{S}_{Q_{sim}}}{\hat{S}_{Q_{obs}}} = \alpha r$
R^2	Coefficient of determination (Krause *et al.*, 2005)	$R^2 = \frac{\sum_{i=1}^{N}(Q_{obs,i} - \bar{Q}_{obs})(Q_{sim,i} - \bar{Q}_{sim})}{\sqrt{\sum_{i=1}^{N}(Q_{obs,i} - \bar{Q}_{obs})^2}\sqrt{\sum_{i=1}^{N}(Q_{sim,i} - \bar{Q}_{sim})^2}}$
VE	Volumetric efficiency (Criss and Winston, 2008)	$VE = 1 - \frac{\sum_{i=1}^{N}\lvert Q_{sim,i} - Q_{obs,i}\rvert}{\sum_{i=1}^{N}Q_{obs,i}}$
IA	Index of agreement (Krause *et al.*, 2005)	$IA = 1 - \frac{\sum_{i=1}^{N}(Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{N}\left(\lvert Q_{obs,i} - \bar{Q}_{obs}\rvert + \lvert Q_{sim,i} - \bar{Q}_{obs}\rvert\right)^2}$
LE	Lindström efficiency coefficient (Seibert and Vis, 2010)	$LE = NSE - 0.1\frac{\sum_{i=1}^{N}\lvert Q_{obs,i} - Q_{sim,i}\rvert}{\sum_{i=1}^{N}Q_{obs,i}}$
KGE_{FDC}	*KGE* computed from: – entire flow duration curve (KGE_{FDC}) (e.g.,Todorović et al., 2019), and – different flow duration curve (FDC) segments. The FDC segments are set after recommendations by Pfannerstill et al. (2014). Segments are obtained from flows that are exceeded given per cent of time of the simulation period.	FDC segments considered: ○ extremely high flows exceeded up to 5% of time (KGE_{0-5}), ○ high flows: exceeded 5-20% of time (KGE_{5-20}), ○ mean flows, exceeded 20-70% of time (KGE_{20-70}), ○ low flows, exceeded 70-95% of time (KGE_{70-95}), ○ very low flows, exceeded 95-100% of time (KGE_{95-100}), ○ overall low flows, exceeded 70-100% of time (KGE_{70-100}).

Hydrologic Signatures

– Various hydrologic signatures are obtained from observed and simulated flows
  - Signatures relevant for climate change impact studies
  - *Annual series* of signatures are obtained

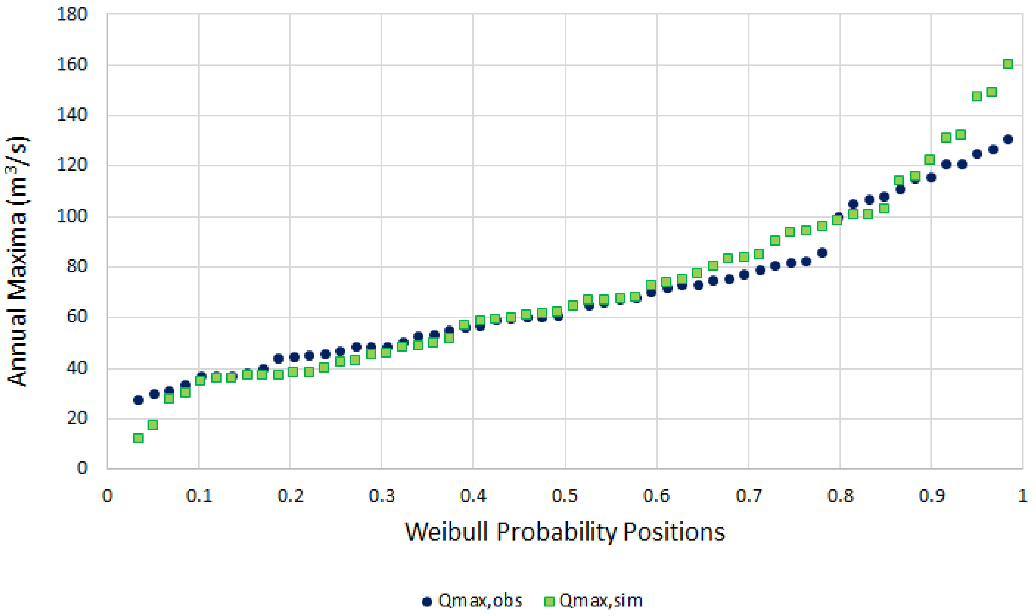
Hydrologic signatures	Description	Reference
Mean annual flow, Q_{mean}	Mean flows in a water year.	
Mean spring flow, Q_{spring}	Series of mean flows in the spring (1st March through 31st May) over the simulation period.	(Chen *et al.*, 2017)
1-, 5- and 30-day maximum annual flows, $Q_{max,d}$ for d=1, 5 and 30	Series of annual maxima obtained from daily flows averaged over 5 and 30-days in each water year of the simulation period.	(Dankers et al., 2014; Vis et al., 2015)
1-,3-, 7-, 10-, 20-, 30- and 90 day minimum flows, $Q_{min,d}$ for d=1, 3, 7, 10, 20 and 30	Series on minimum flows averaged over a given number of days (d) obtained in each water year of the simulation period.	(Richter et al., 1996; Olden and Poff, 2003; Garcia et al., 2017)
10th and 90th flow percentiles in wet seasons, $Q_{wet,10p}$ and $Q_{wet,90p}$	Series of specific flow percentiles obtained in each water year of the simulation period. Wet season is defined as period from 1st April through 30th September.	(Yarnell *et al.*, 2020)
10th and 90th flow percentiles in dry seasons, $Q_{dry,10p}$ and $Q_{dry,90p}$	Series of specific flow percentiles obtained in each water year of the simulation period. Dry season is defined as period from 1st October through 31st March.	(Yarnell *et al.*, 2020)
Timing of the centre of mass of annual flow, *COM*	Timing is computed from daily flows Q_i and for each year in a simulation period: $COM = \frac{\sum_i Q_i t_i}{\sum_i Q_i}$ where t_i represents ordinal day of a water year.	(Mendoza et al., 2015; Kormos et al., 2016)
Spring onset (spring "pulse day"), *SPD*	Spring onset is the ordinal number of the day in which the negative difference between the streamflow mass curve and the mean streamflow mass curve is the greatest. Spring onset series is obtained from values in each water year of a simulation period.	(Cunderlik and Ouarda, 2009)
High flow frequency, *HFF*	Series of mean number of days in a water year with flows greater than 5 times the mean observed flow in the simulation period. In the literature, flows greater than 9 times the mean observed flow are used for high flow frequency computations. Since the considered catchments in this paper exhibited relatively low flow variability, this threshold was reduced to 5.	(Westerberg and McMillan, 2015; Krysanova et al., 2017)
Low-flow frequency, *LFF*	Series of mean number of days in a water year with flows smaller than 20% of the mean observed flow in the simulation period.	(Nicolle et al., 2014; Westerberg and McMillan, 2015; Krysanova *et al.*, 2017)
Timing of the maximum annual flow, T_{Qmax}	Ordinal days in which maximum annual flow occurred, obtained in each water year of the simulation period.	(Richter *et al.*, 1996)
Timing of the minimum annual flow, T_{Qmin}	Ordinal days in which minimum annual flow occurred, obtained in each water year of the simulation period. If there are several consecutive days with the same minimum flows, the mean timing of these days in a water year is adopted.	(Vis et al., 2015; Parajka et al., 2016)



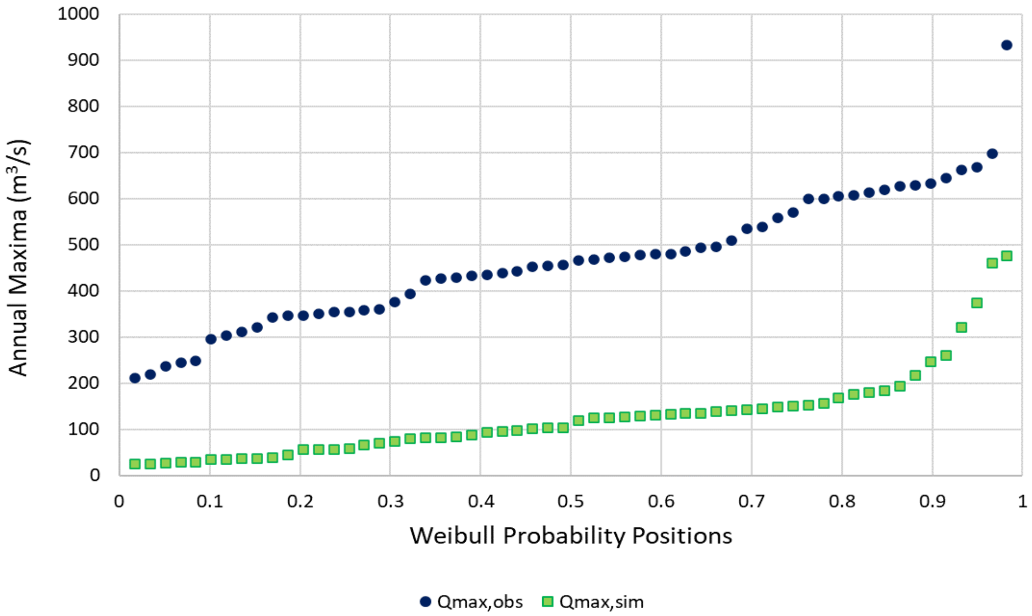
Accuracy in Reproducing Signatures - Distributions

- Wilcoxon rank sum test is used to compare annual series of signatures (e.g., annual maxima) obtained from observed and simulated series
  - If the test null hypothesis is not rejected at 5% level of significance – model properly reproduces distribution of a signature

Test null hypothesis not rejected



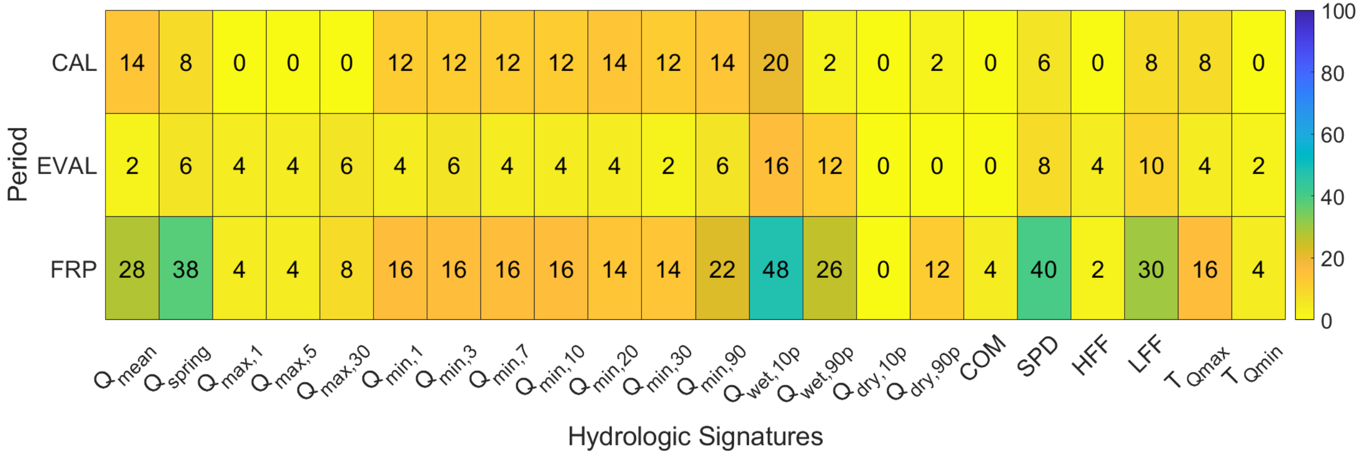
Test null hypothesis rejected



Accuracy in Reproducing Signatures - Trends

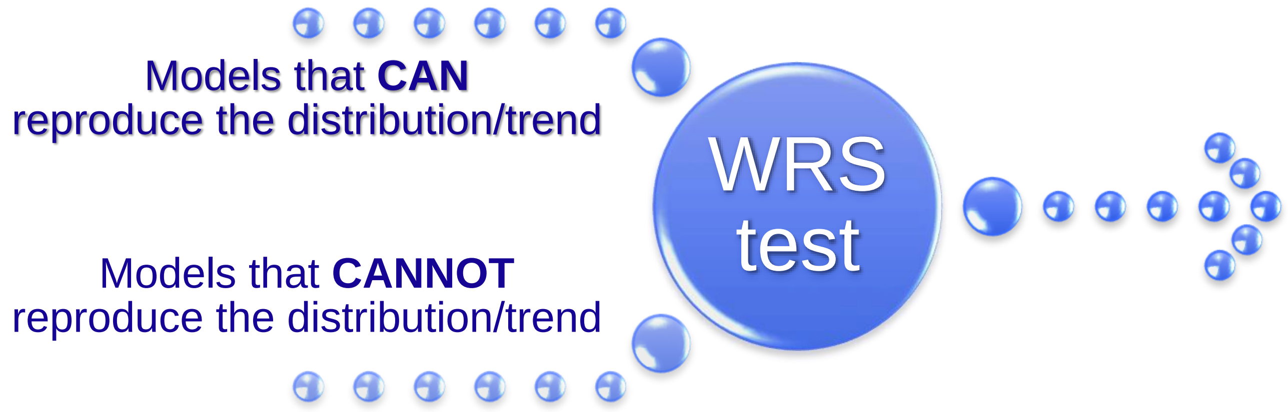
- Trends in annual series of signatures are tested with the Mann-Kendall test
  - Sign of trends: the Sens' slope estimator
- The model properly reproduces trends in the signature if:
  - ➢ Trends in neither of series of signature (obtained from observed and simulated flows) are significant at 5% level of significance
    (the null hypothesis of the Mann-Kendall test is not rejected at 5% level of significance)
  - ➢ Trends in both series of signature are significant and of the same sign

% of catchments with significant trends in signatures obtained from *observed* flows



Informativeness of Performance Indicators

1. Models are divided in two groups: models that *can* and *cannot* reproduce distribution or trend in a specific signature
2. *Performance indicators* of the two groups are compared with the Wilcoxon rank sum test
   - This procedure is repeated for all hydrologic signatures



<u>Results of the Analysis:</u>

2: well reproduced in all catchments

1: H0 of the test is rejected; *indicator <u>is</u> informative*

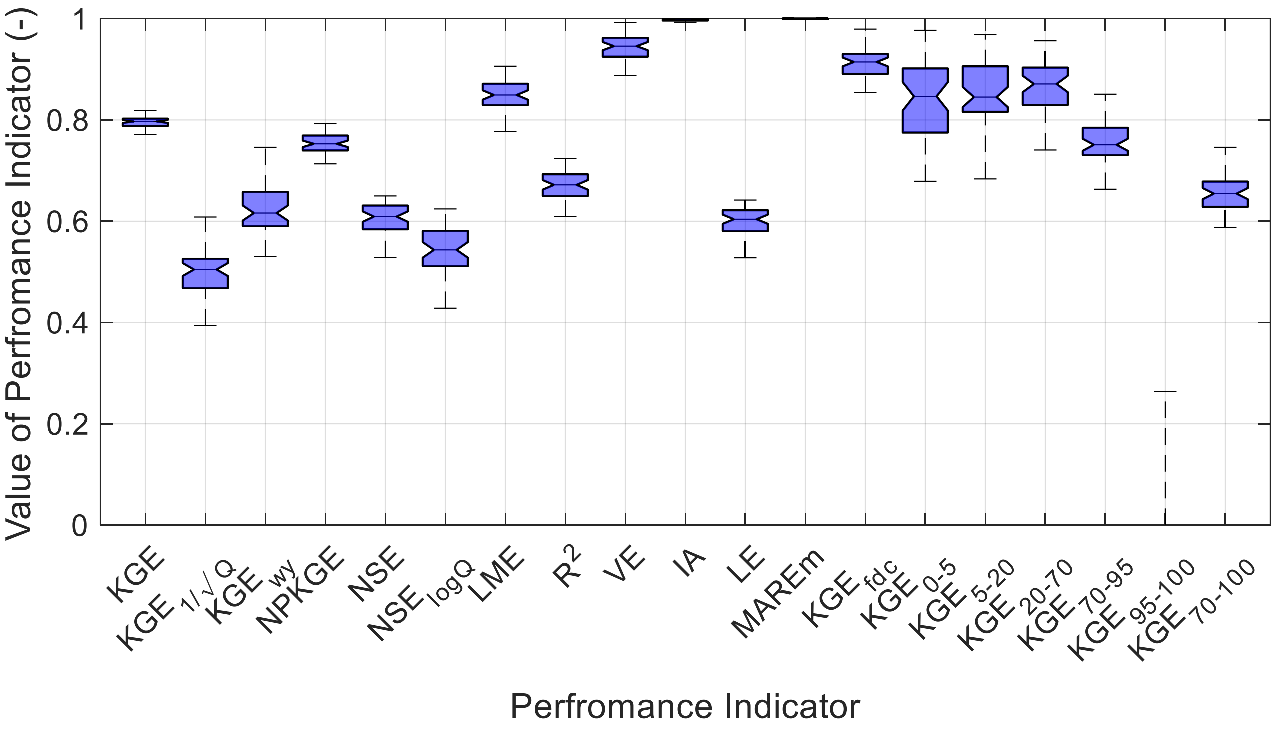
-1: H0 is not rejected; *indicator <u>is not</u> informative*

- 2: reproduced in none of the catchments

Parameter Equifinality

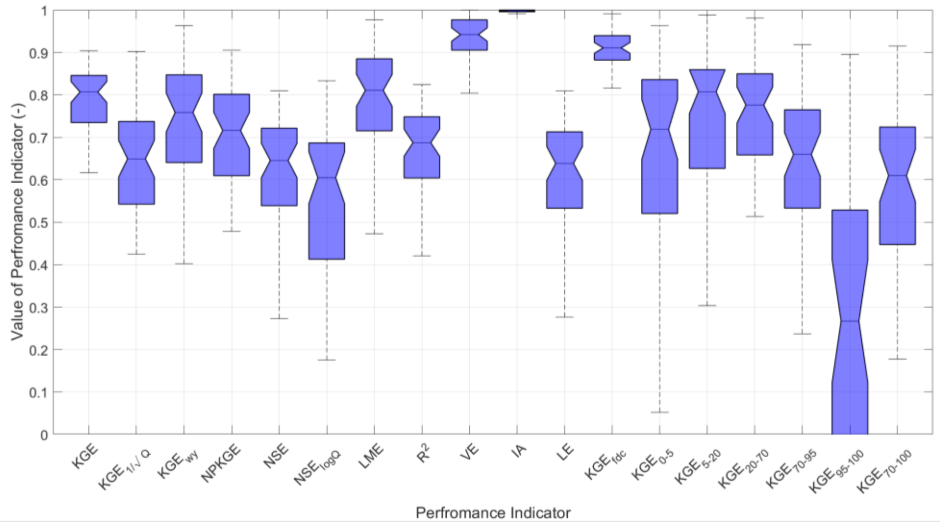
- Does equifinality in performance indicators implies equifinality in distributions and trends in the series of signatures?
  - Analyses of the parameter equifinality: 50 best sets (out of 75,000 randomly sampled ones) according to *OF* are selected

Performance indicators with the 50 best parameter sets in the Assembro catchment in the calibration period

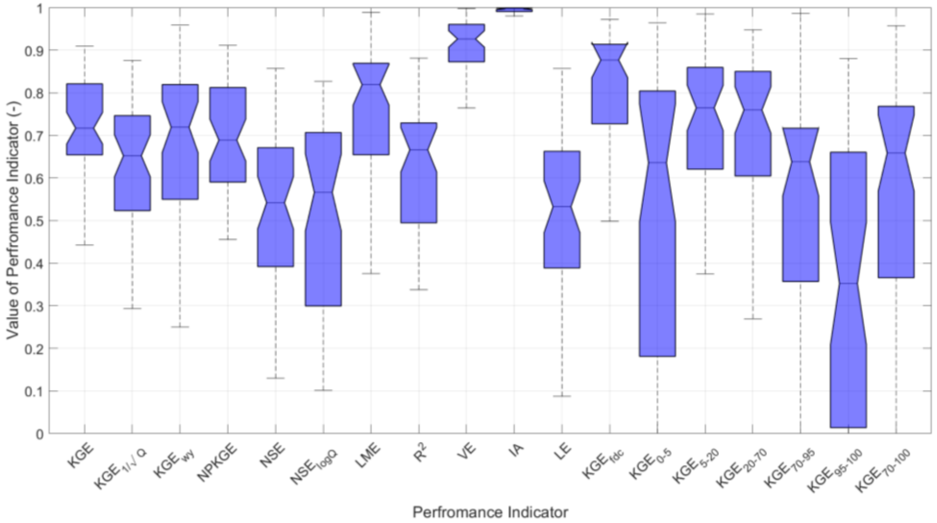


Performance Indicators in the Selected Catchments

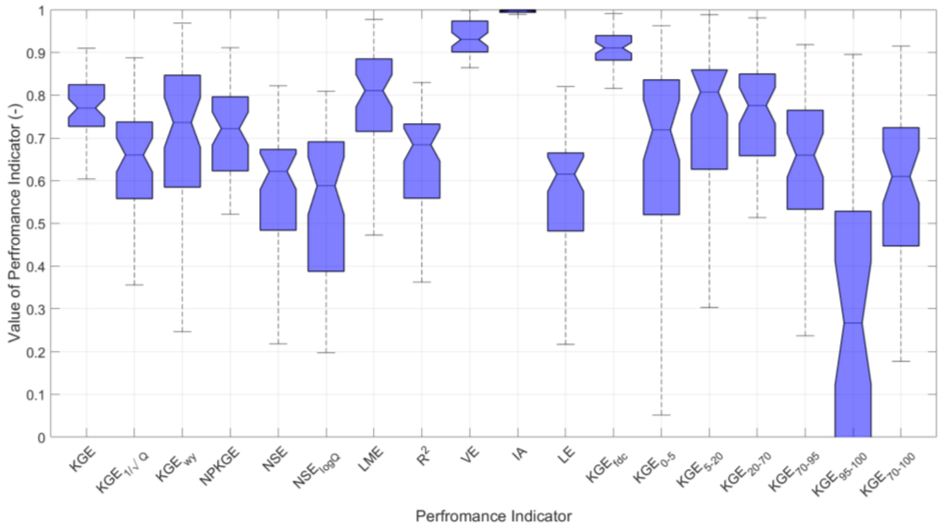
Calibration



Evaluation



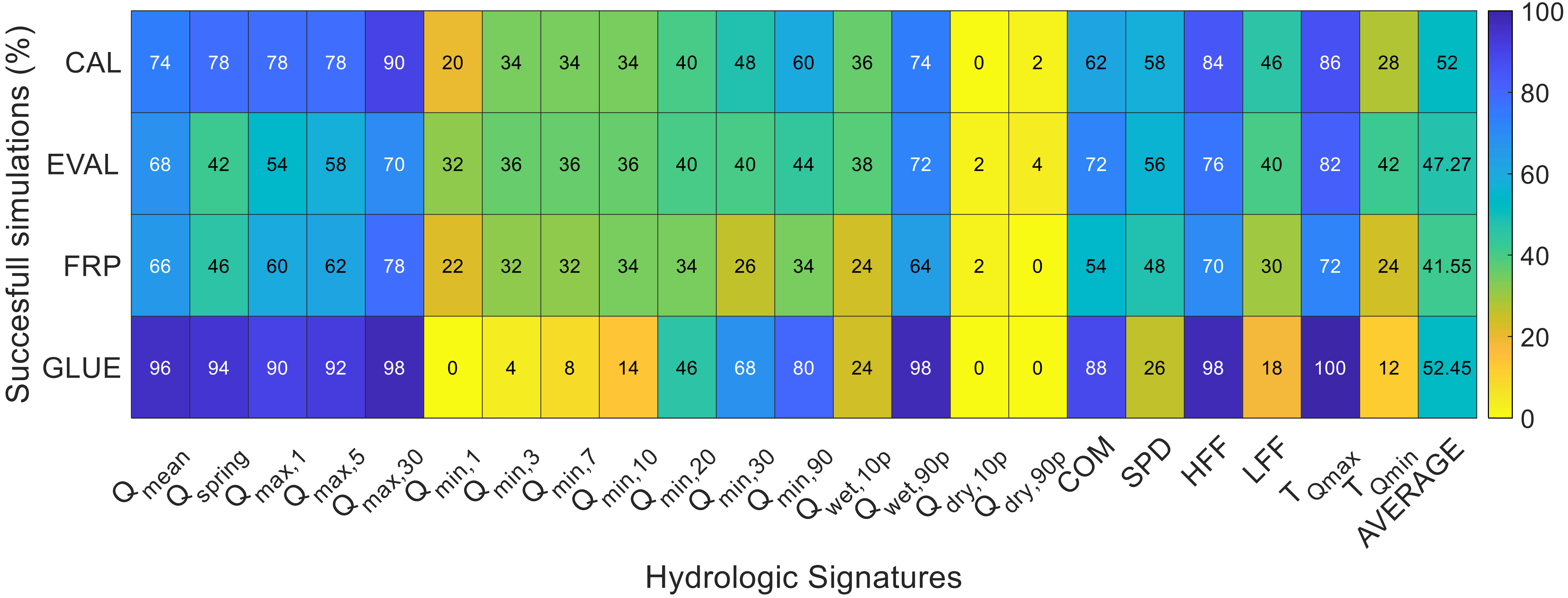
Full record period



Performance in Reproducing Signatures – Distributions

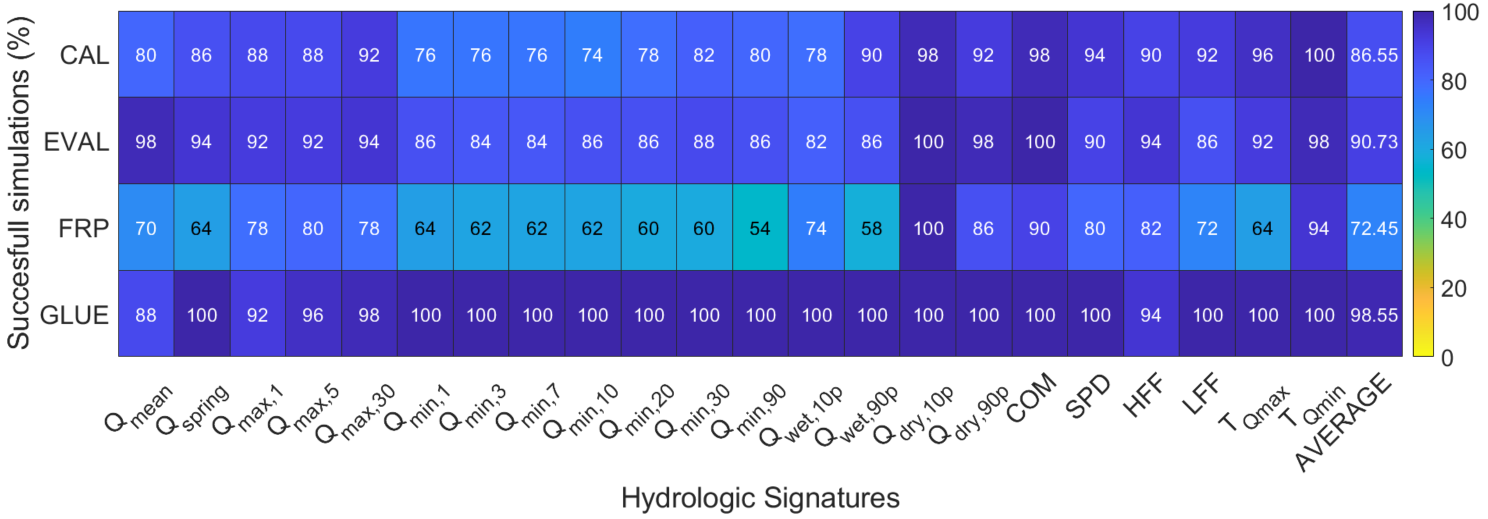
- Performance varies across the signatures
  - Poor performance in low flows

% of simulations with well-reproduced distributions

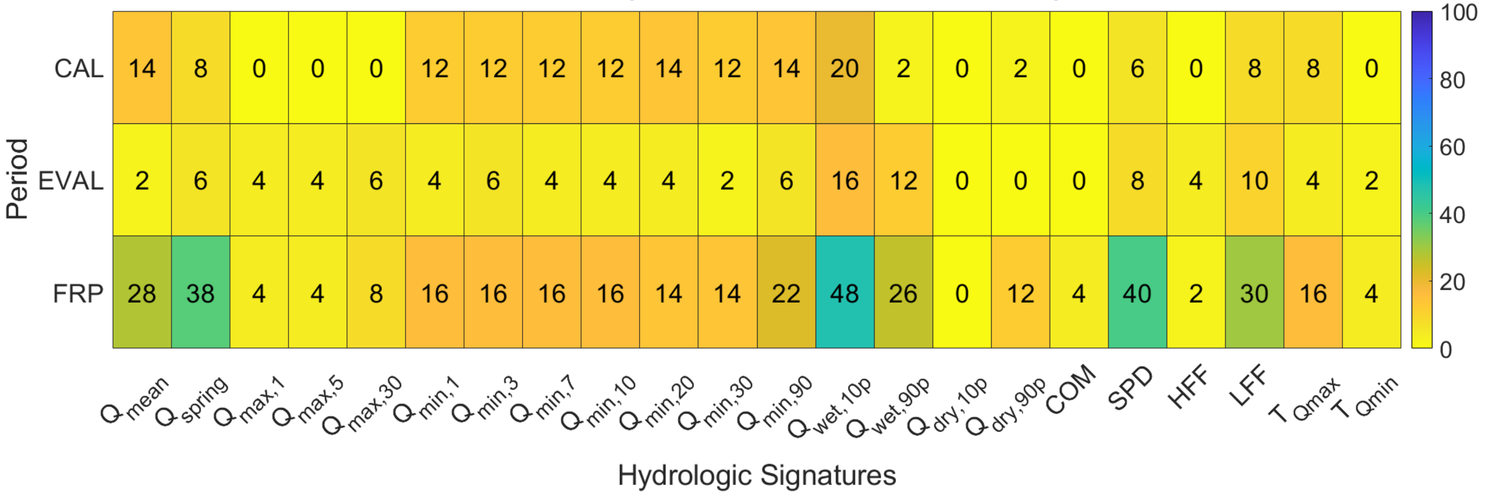


Performance in Reproducing Signatures – Trends

% of catchments in which trend in series of the signature is well reproduced



% of catchments with significant trends in signatures



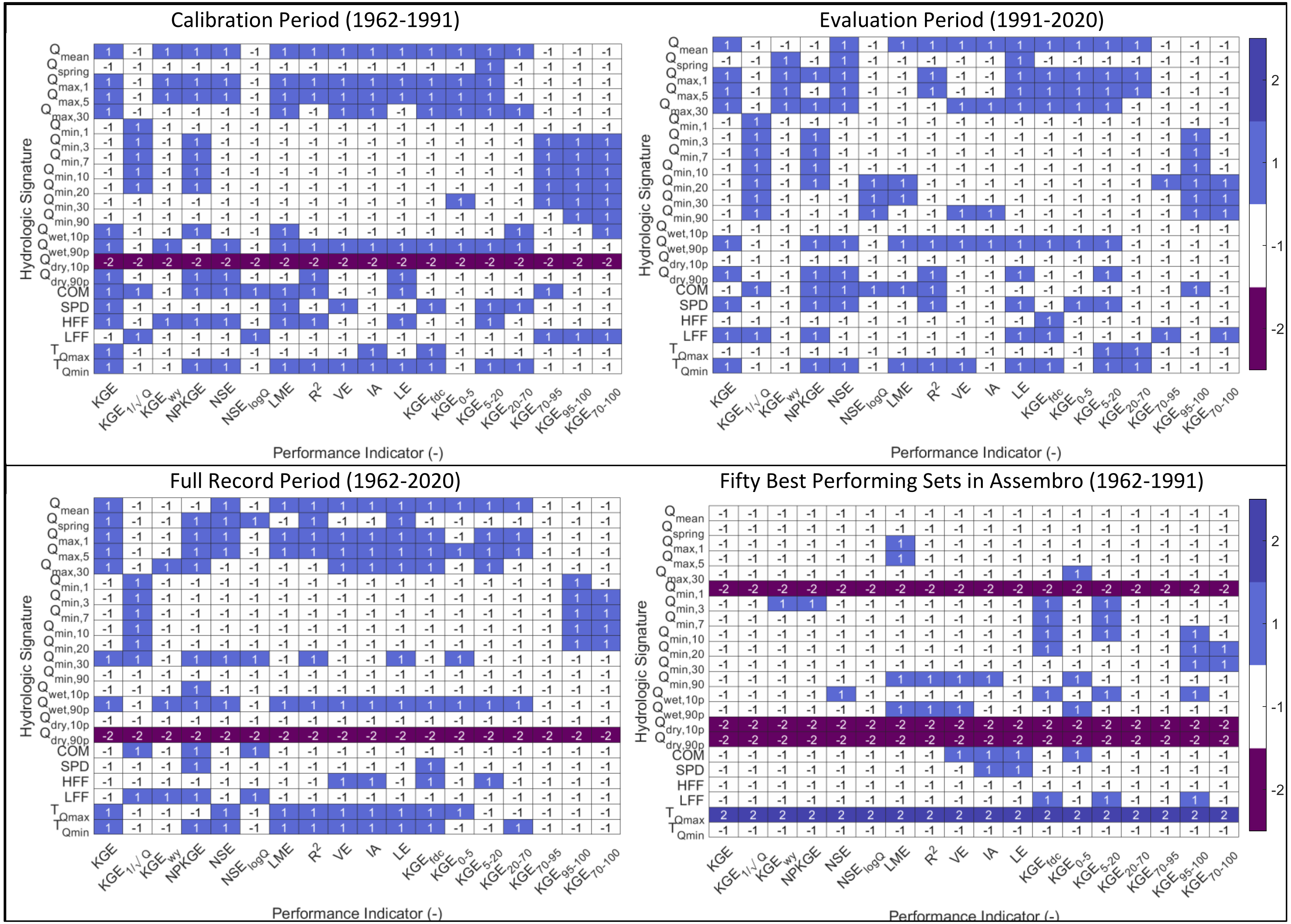
Informativeness of Indicators – Signatures' Distributions

2: well reproduced in all catchments

1: *indicator <u>is</u> informative*

-1: *indicator <u>is not</u> informative*

- 2: reproduced in none
of the catchments



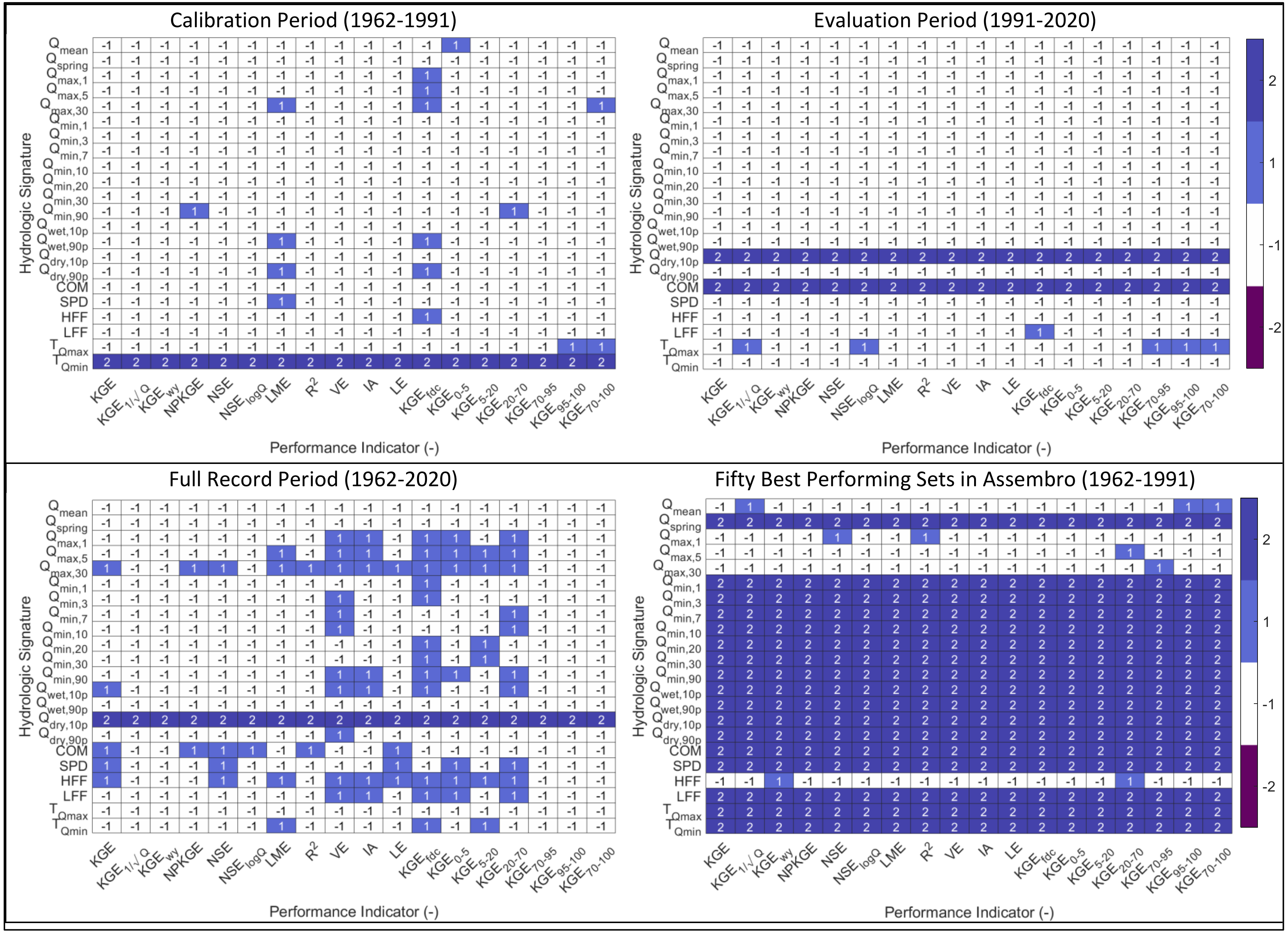
Informativeness of Indicators – Trends in Signatures

2: well reproduced in all catchments

1: *indicator <u>is</u> informative*

-1: *indicator <u>is not</u> informative*

- 2: reproduced in none of the catchments



Conclusions

– Performance in reproducing the distributions varies with the signatures, while it is high in reproducing trends in signatures

– Performance indicators are not necessarily informative about model ability to reproduce distributions or trends in hydrologic signatures

- ➢ These are two distinct and complementary aspects of model performance
- ➢ "*There are a lot of 'good' models that pretend to be suitable for impact studies, and the number of such models grows like a snowball*" (Gelfan and Millionshchikova, 2018)

→ Model evaluation and selection protocols should take into account performance in reproducing distributions and trends in hydrologic signatures

Todorović et al. (2022), under review for Hydrological Sciences Journal

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