Supplementary Information

for

Hybrid approaches enhance hydrological model usability for local streamflow prediction

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Table S1: Summary of dominant hydrological processes of predefined hydrological clusters, including the geographical domain that are mostly located (presented below in square brackets), according to Pechlivanidis et al. (2020).

Hydrological cluster	**Description of hydrological processes and their location**
1	- Baseflow-controlled streamflow - Unresponsive to precipitation due to large rivers and water bodies - Some influence of snowmelt [Poland and Denmark]
2	- Precipitation-driven streamflow - Frequent peak flows with long recessions [France, Germany, south Finland, Sweden and Russia]
3	- High interannual variability - Snow-dominated regime with significant spring snowmelt - Dampened streamflow due to lakes, wetlands, and low evapotranspiration [North-central and north-western Russia]
4	- High precipitation with very responsive streamflow - Flow regulated for hydropower in winter - Tendency for spring streamflow [Elevated regions in Norway, Alps, Iceland, Spain, western Ireland and western UK]
5	- Highly variable streamflow regime - Responses driven by snowmelt and precipitation [Portugal, Spain, Italy, Greece, Turkey, and mountainous areas of Norway, Sweden, Finland and Russia]
6	- Highly variable streamflow - Quick response to precipitation - Long recessions

	[Southern and central Europe, and south Scandinavia]
7	- Elevated basins with high streamflow variability - Flashy responses to precipitation - High runoff coefficients due to low evapotranspiration [Spain, Italy, Albania and Greece]
8	- Baseflow-dominated hydrographs with sharp rising limbs - Small annual variability [Central Europe]
9	- Highly baseflow-dominated streamflow - Minimal response to precipitation [Scandinavia, Russia and spread around Europe]
10	- Low elevation basins with very low year-round streamflows - Low runoff coefficients [Portugal, Spain, Greece and Turkey]
11	- Low runoff coefficients - High annual variability with fast response and recession - Potential human impacts (e.g., irrigation) [Eastern Ukraine and south-eastern Russia]

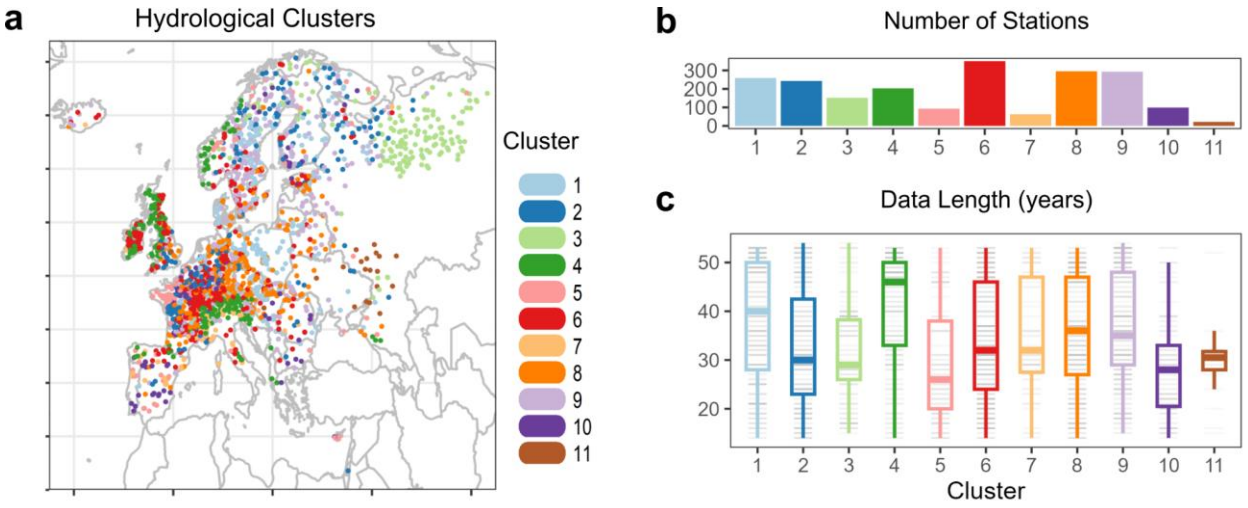

Fig. S1: Properties of available local observations and model-based hydrological clusters. a, Clusters of hydrological similarity identified based on the process-based E-HYPE model. **b-c,** Number of stations within each hydrological cluster (b), and corresponding data length (c).

Table S2: Median evaluation metrics of model configurations using observed streamflow (obs) and residuals as target variables. The configuration with the highest performance is highlighted in bold with a green background and is selected for further analysis in this study.

	median MAE		median NSE		median logNSE	
Target	obs	residual	obs	residual	obs	residual
E-HYPE	0.432		0.362		0.361	
+QM	0.361	---	0.441	---	0.477	---
+GLM	**0.356**	0.382	**0.527**	0.437	**0.509**	0.480
+RF	**0.346**	0.400	**0.533**	0.387	**0.582**	0.468
+LSTM	0.352	**0.348**	**0.579**	**0.579**	0.452	**0.590**

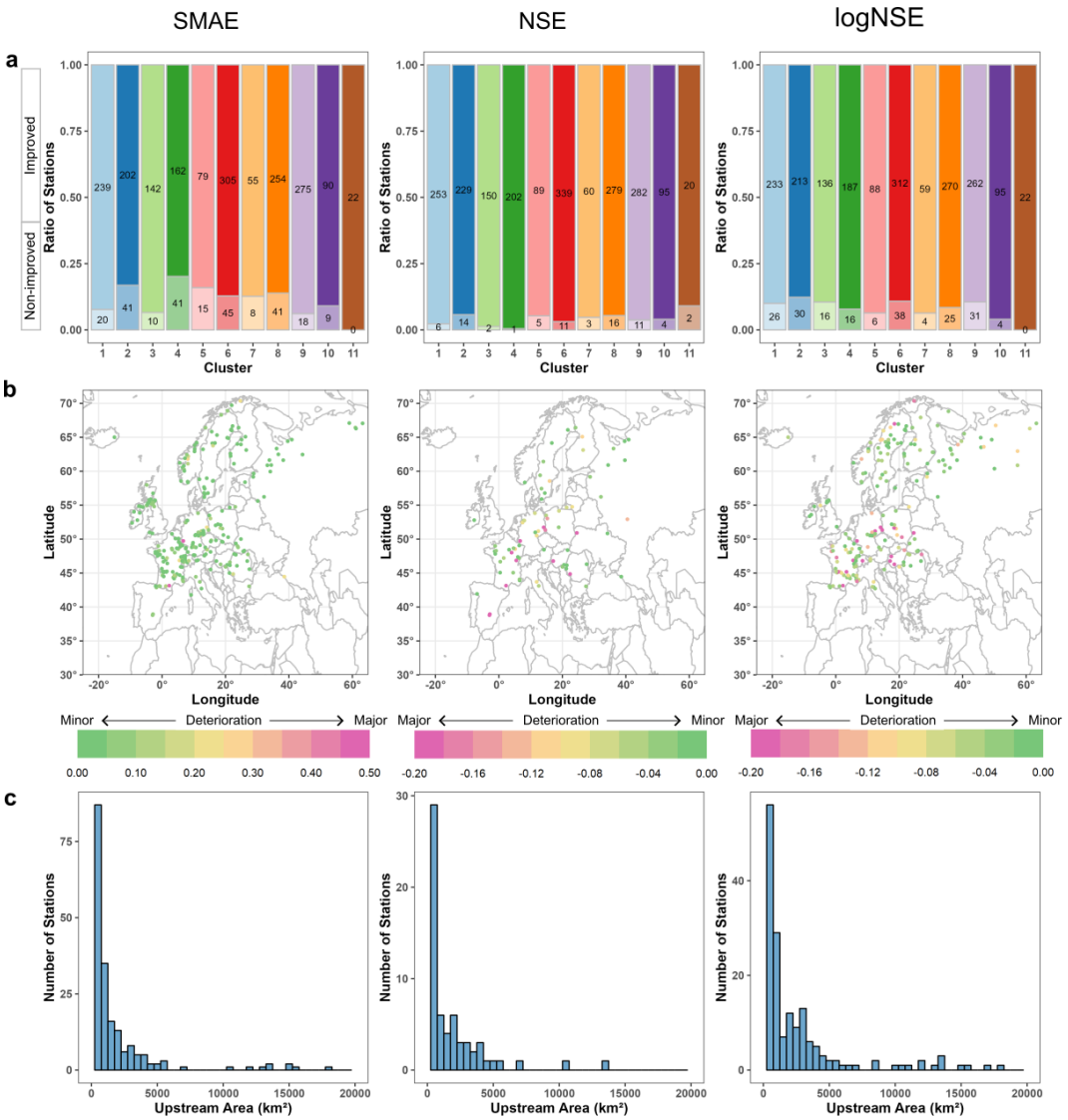

Fig. S2: Performance and characteristics of stations with no improvement from the hybrid modelling approach in terms of total volume, high and low streamflow extremes. a, ratios of improved/non-improved stations in each predefined hydrological cluster with numbers denoting the actual number of stations. The clusters are used to represent hydrological similarity, detailed information for each cluster can be found in Table S1. **b**, performance deterioration in the non-improved stations (performance difference between the process-based E-HYPE model and the best performing hybrid model). **c**, frequency distribution of upstream area at the non-improved stations.

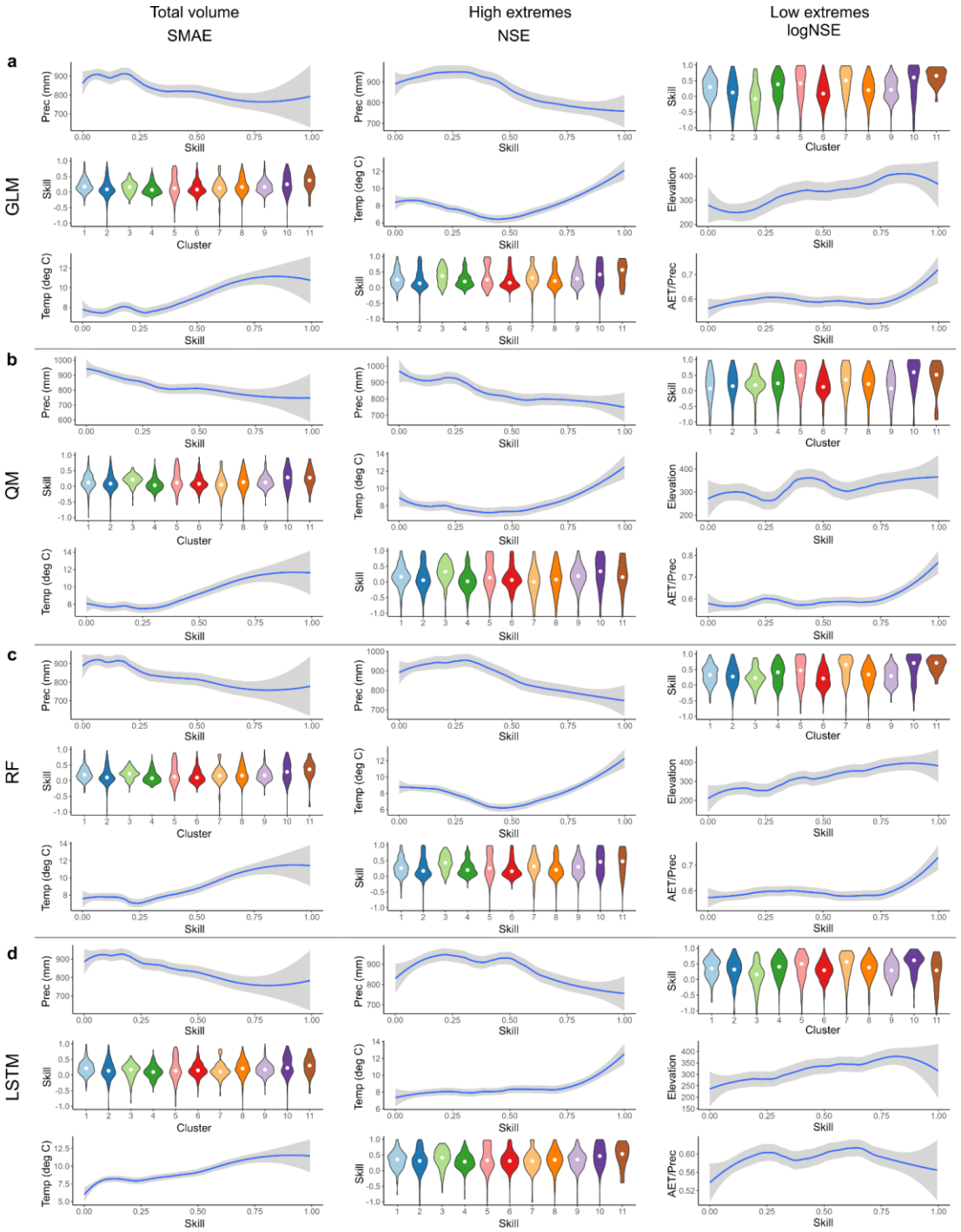

Fig. S3: Skill variation as a function of the top identified drivers in terms of total volume - SMAE, high streamflow extreme - NSE, and low streamflow extreme - logNSE for the hybrid models. **a**, E-HYPE-GLM method; **b**, E-HYPE-QM method; **c**, E-HYPE-RF method; **d**, E-HYPE-LSTM method.

Supplementary References

Pechlivanidis, I. G., Crochemore, L., Rosberg, J. & Bosshard, T. What Are the Key Drivers Controlling the Quality of Seasonal Streamflow Forecasts? *Water Resour. Res.* **56**, e2019WR026987 (2020).