



Supplement of

Groundwater head responses to droughts across Germany

Pia Ebeling et al.

Correspondence to: Pia Ebeling (pia.ebeling@ufz.de)

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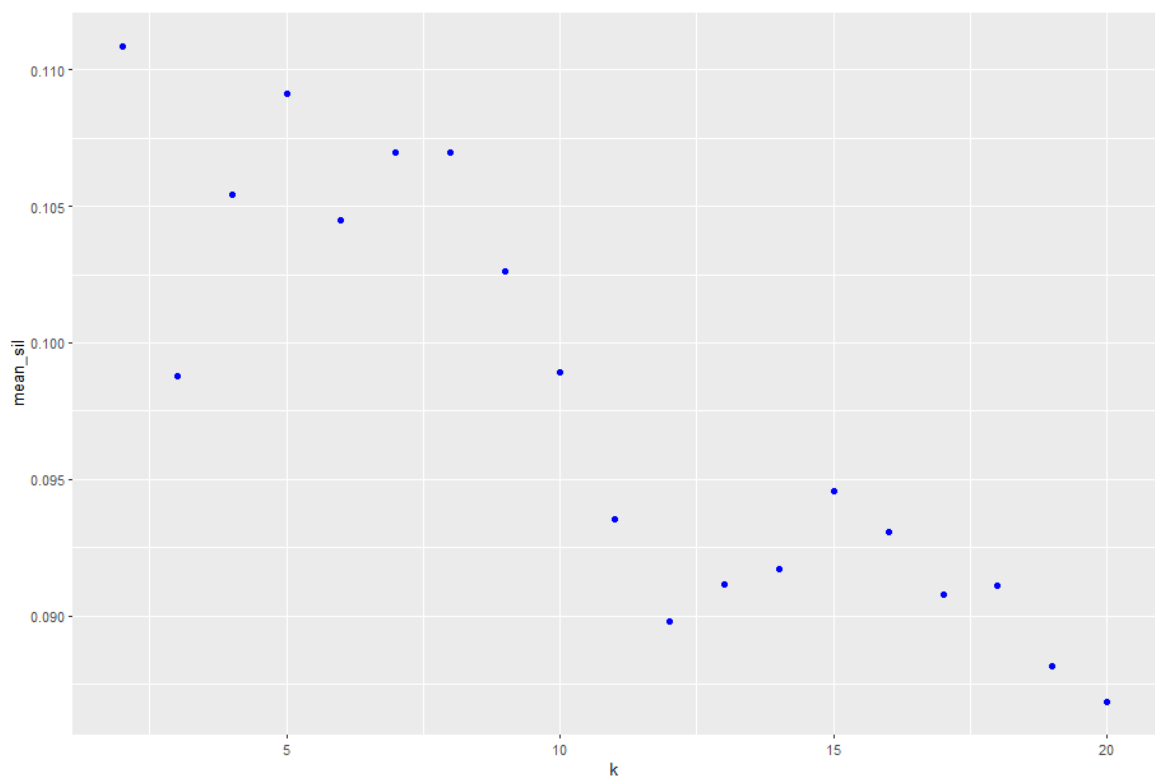


Figure S1: Mean silhouette distance against the number of clusters (k) to identify optimal number of clusters for kmeans clustering. Local maxima occur at k=2, k=5, and k=8. Please, refer to Section 2.3 in the manuscript.

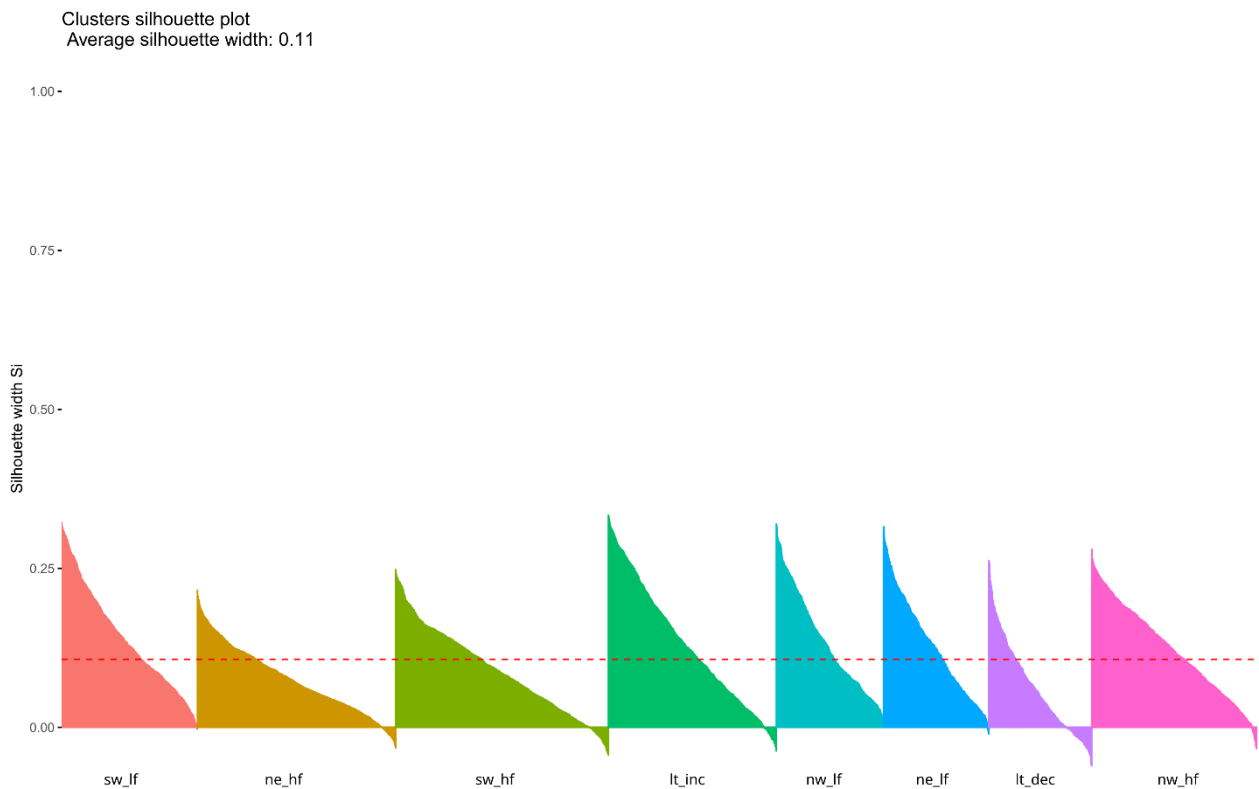


Figure S2: Silhouette distances of individual members across the different clusters for $k=8$. The dashed vertical line marks the mean silhouette distance. The silhouette width ranges from -1 to 1. A positive value indicates that the member is closer to its assigned cluster than to the neighboring one, a value of 0 indicates the member is exactly in between two clusters and a negative value indicates the member is “closer” to the neighboring cluster than its assigned one. For more information, please, refer to Section 2.3 in the manuscript.

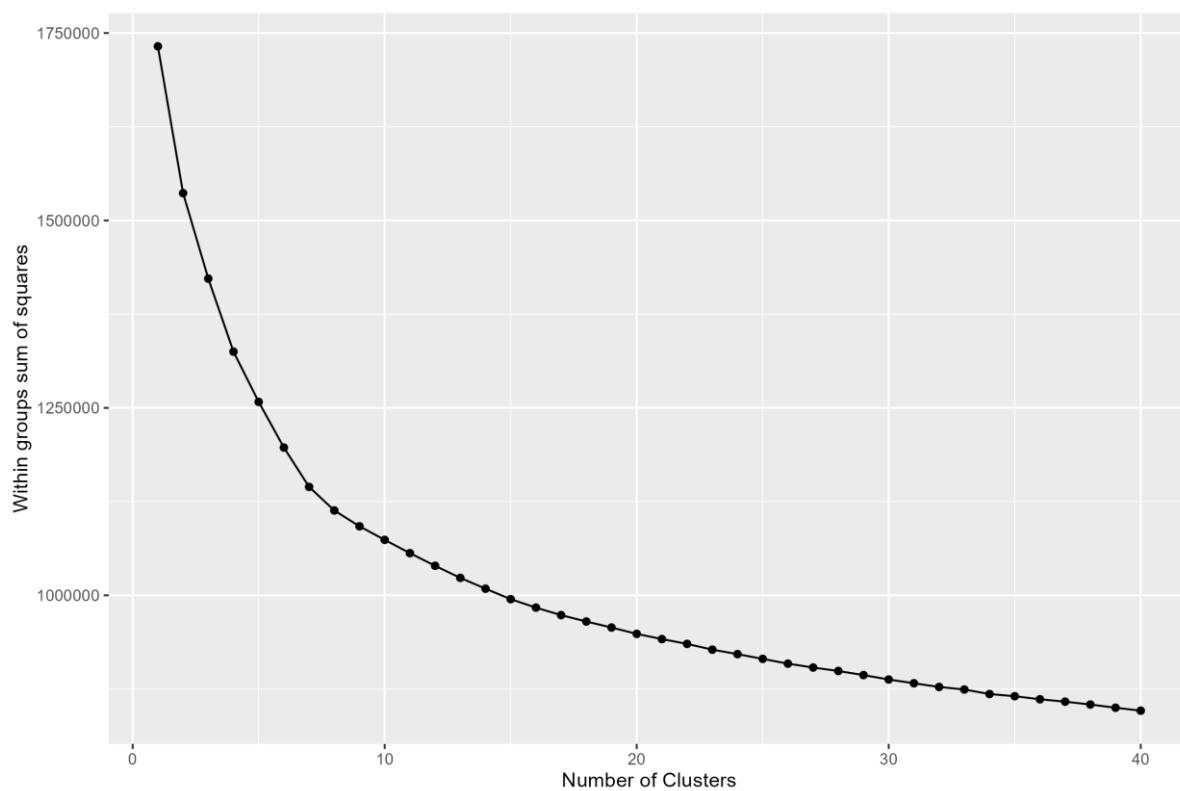


Figure S3: “Elbow plot” (or scree plot) with the sum of squares against the number of clusters (k), used to identify the optimal number of clusters for kmeans clustering. Please, refer to Section 2.3 in the manuscript.

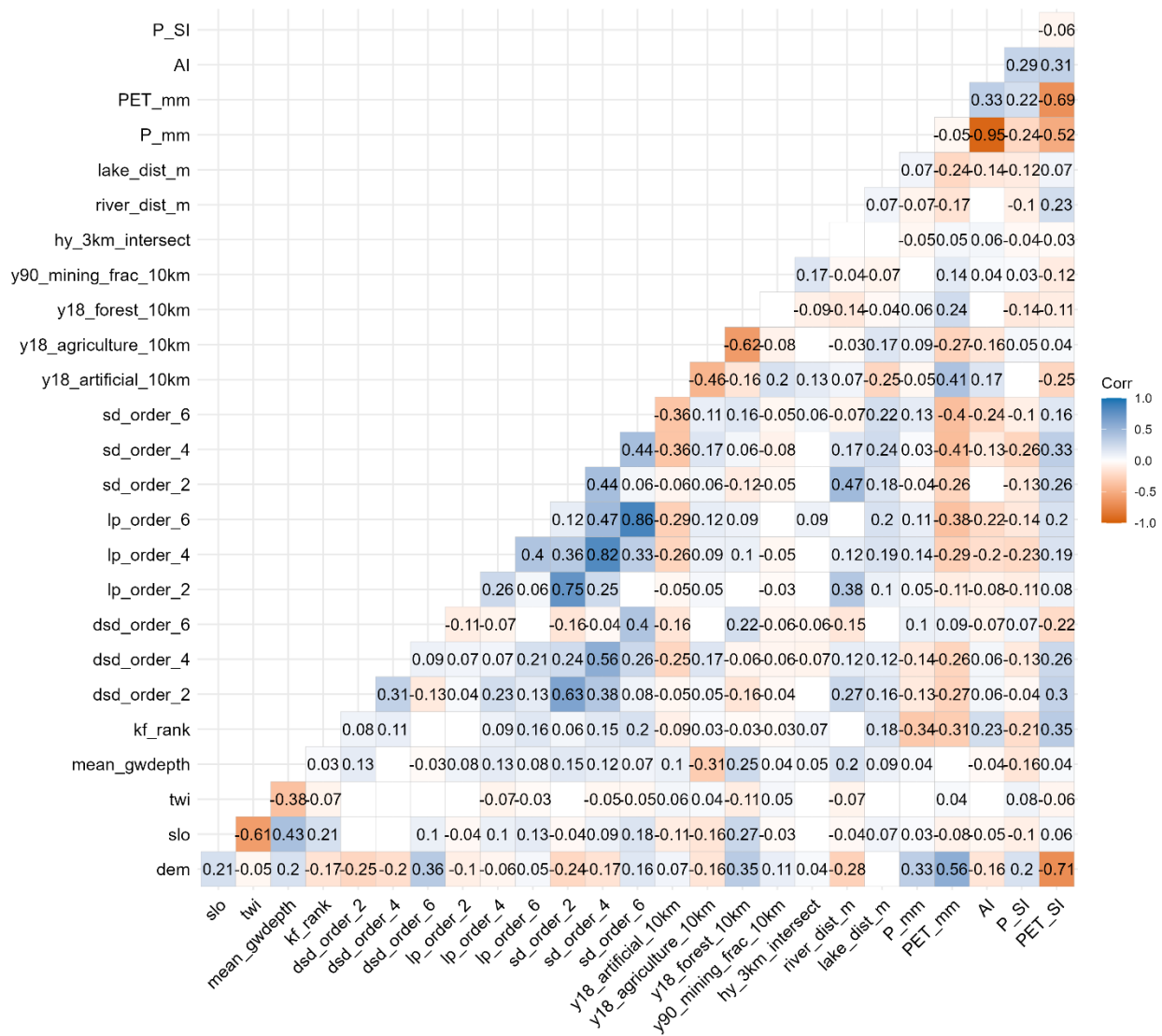


Figure S4: Spearman rank correlation among spatial properties across the 6626 groundwater wells. The colors and labels indicate the value of the correlation coefficient, blank cells refer to non-significant correlations (p-value > 0.05) The spatial properties including the methods and units are described in Table 2 of the main manuscript.

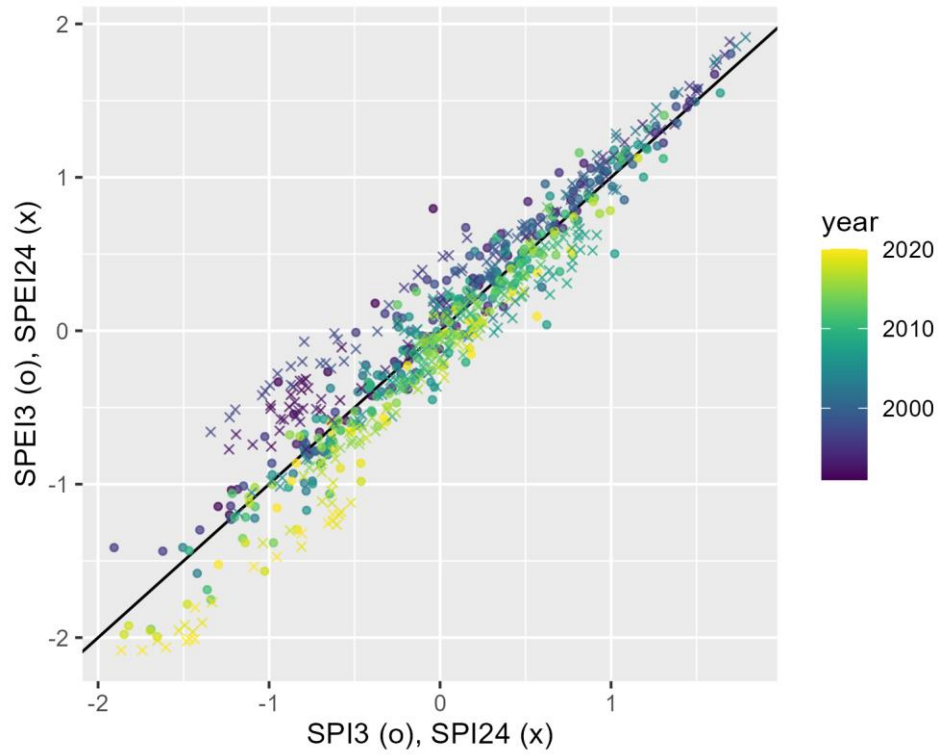


Figure S5: Differences between average SPI and SPEI for short-term accumulation period of 3 months (circles) and long accumulation of 24 months (crosses) with colors according to the year. It can be seen that SPEI is generally higher at the beginning of the 30-year period and lower at the end, corresponding to negative overall trends.

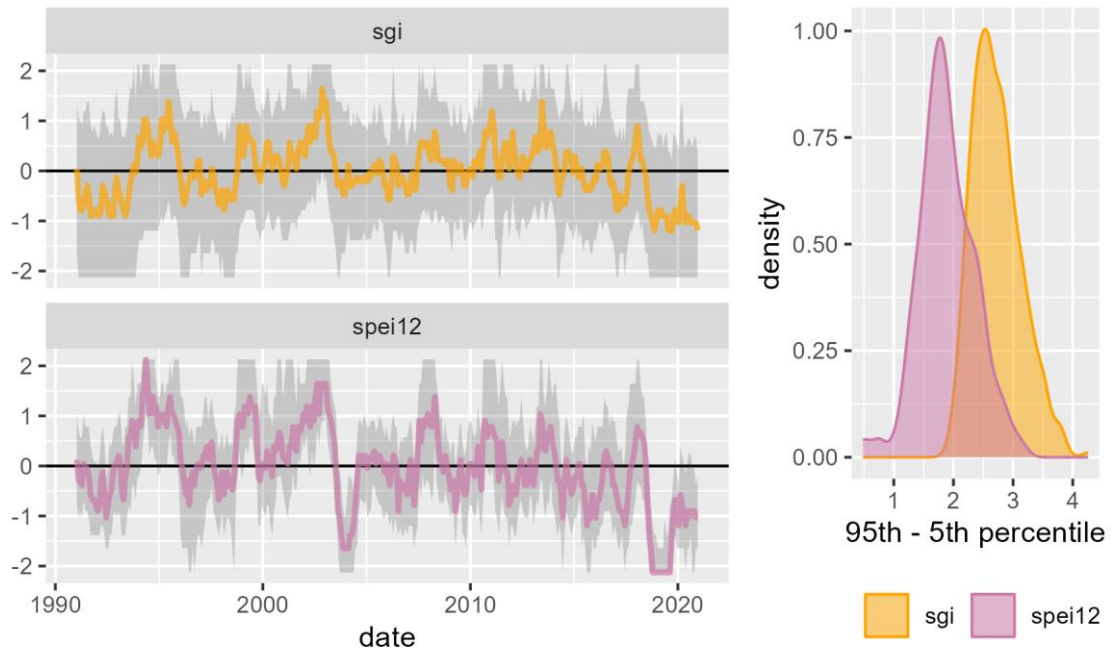
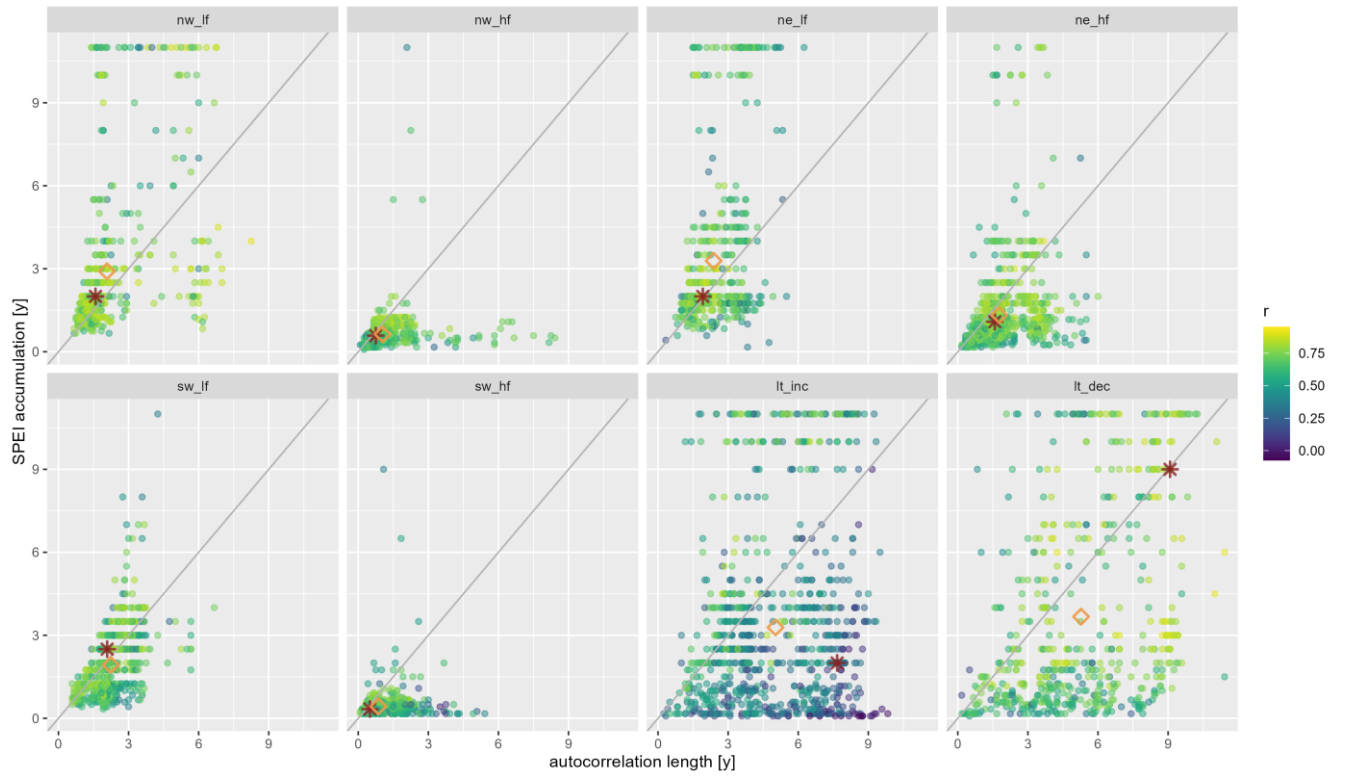


Figure S6: Median SGI and SPEI₁₂ time series across all wells with the band between the 95th and 5th percentile in gray (left) and density distribution of the bandwidths between the 95th and 5th percentile (right).



45 **Figure S7: Groundwater response time scales (SPEI accumulation acc_{SPEI}) against autocorrelation length (acf_lag) of individual wells per cluster, of cluster centers (brown star) and mean across cluster members (orange diamond). Colors indicate the cross-correlation coefficients between SGI and $SPEI_{max}$.**

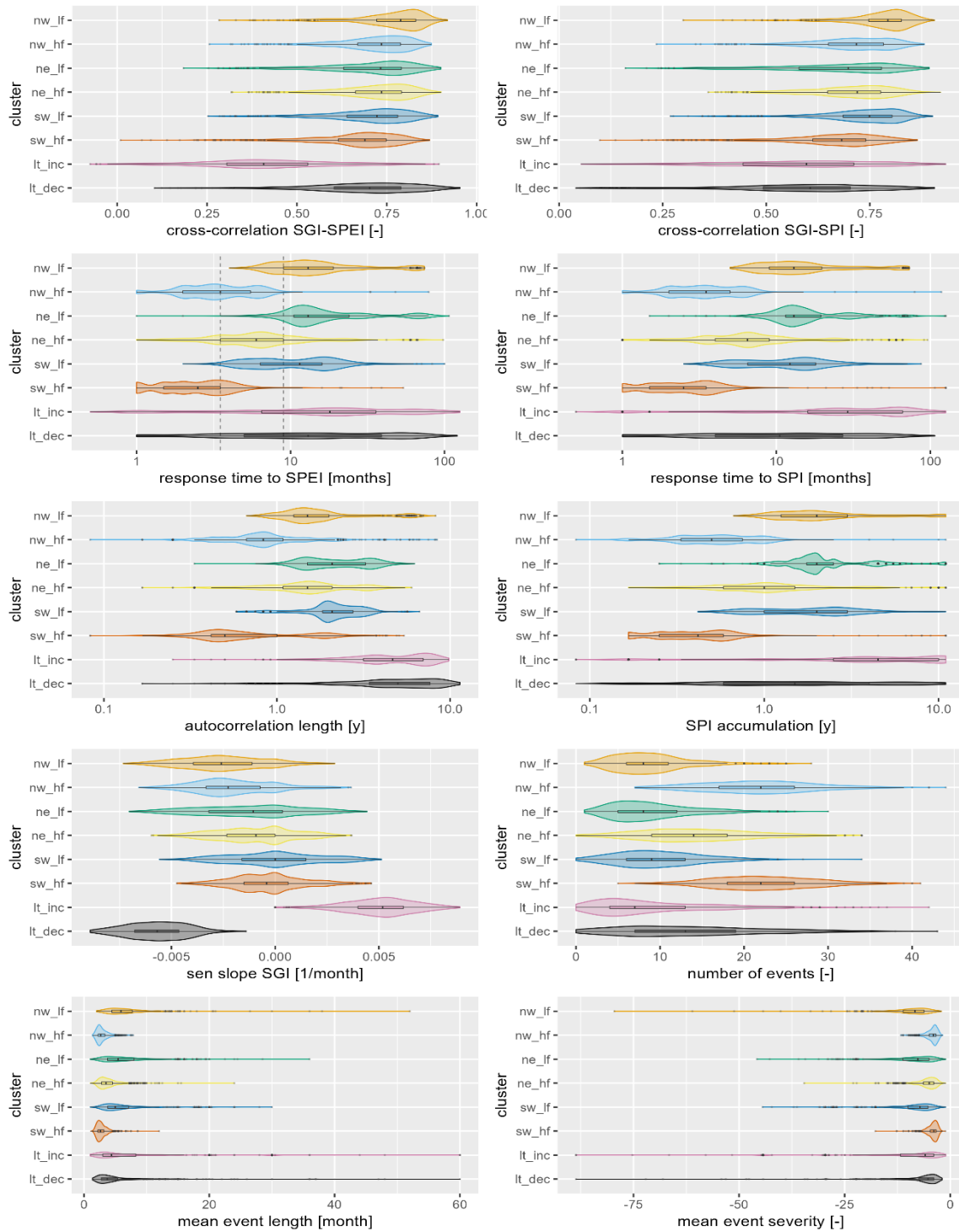


Figure S8: Distribution of groundwater response characteristics per cluster as violin plots with additional boxplots visualizing summary statistics (median, the 25th and 75th percentiles). Dashed lines indicate the thresholds in response time to SPEI ($\text{respt}_{\text{SPEI}}$) for short- (≤ 3.5) and long-term (> 9) vulnerability classes (Section 3.4 and 4.3)

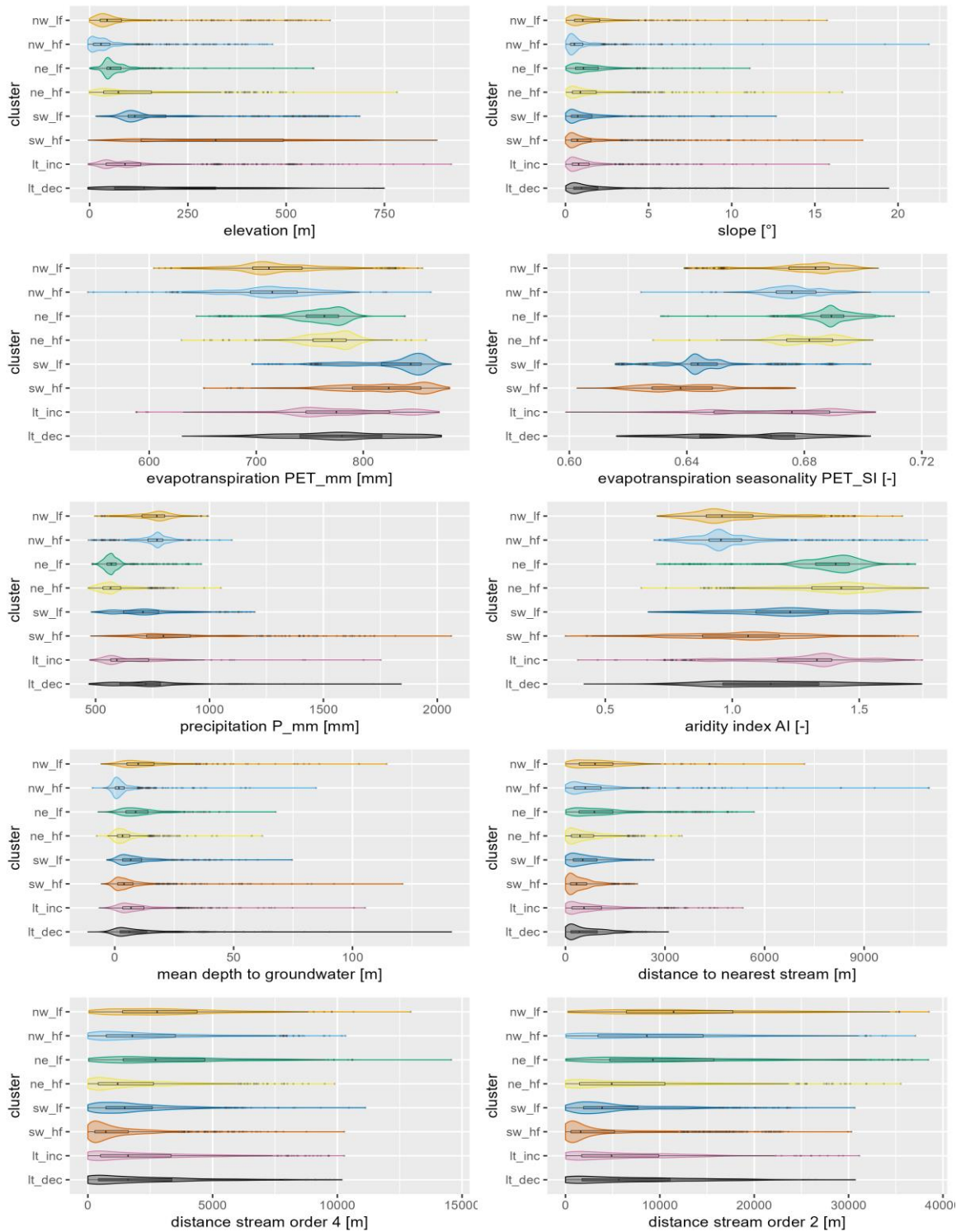


Figure S9: Distribution of spatial controls per cluster as violin plots with additional boxplots visualizing summary statistics (median, the 25th and 75th percentiles).

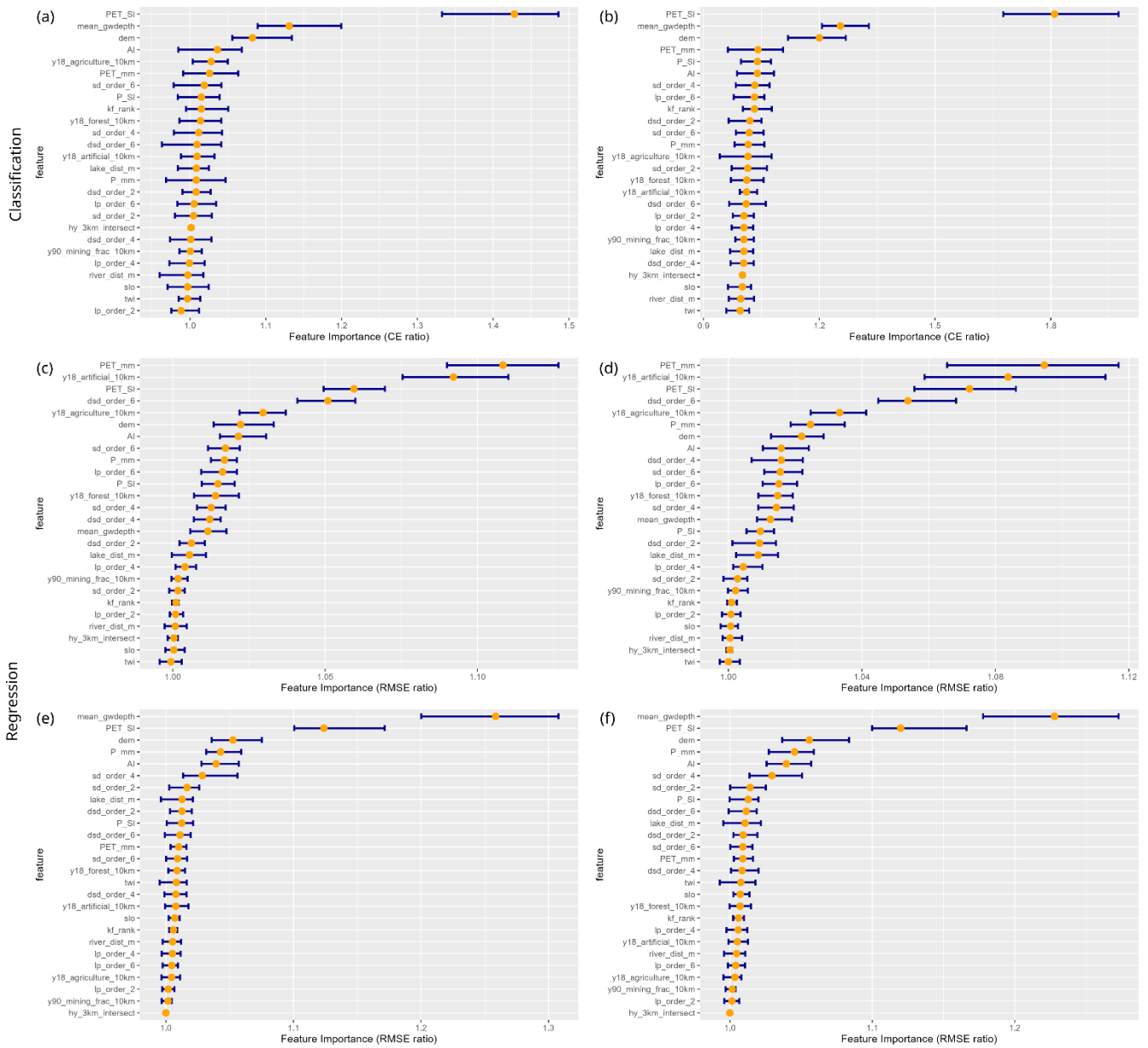


Figure S10: Feature importance of classification and regression models presented in Table 3 for (a) all 8 clusters, (b) the six regional clusters, (c) the trend in residuals between SGI and $SPEI_{acc}$, (d) the trend in residuals between SGI and SPI_{acc} , (e) the response time $respt_{SPEI}$, and (f) the optimal accumulation time acc_{SPEI} . Note: The importance for classification is measured by the classification error (CE) with permutation over the CE without permutation of the respective feature, while for regression the root mean square error (RMSE) was used. The orange dot marks the average feature importance calculated as the mean across the five cross-validation resamplings, i.e. the medians from the 10 permutations applied for each resampling (iteration). The blue bar marks the range between the minimum of the 5th percentile and the maximum of the 95th percentile of importance values (percentiles are from the 10 permutations of each iteration).

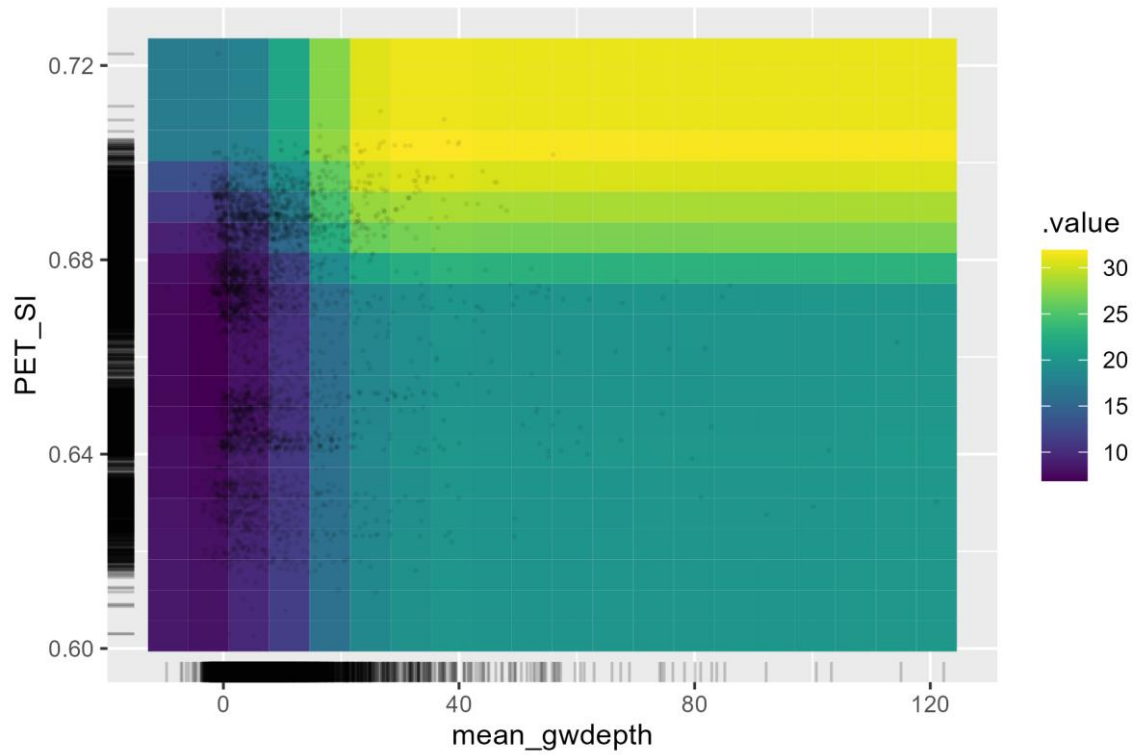


Figure S11: 2D partial dependence plot (PDP) of the effects of mean_gwdepth and PET_SI on the predicted $\text{respt}_{\text{SPEI}}$ for the 6-cluster data subset RF regression model. Note: Marginal plots and black dots show the data distribution across the variable space.

Table S1: Random forest (RF) results including the three most important features from permutation. Performance is given as mean accuracy for classification and coefficient of variation (R^2) for regression models across the cross-validation iterations. Note: All models are shown to complement models (here bold) presented in the main text in Table 3, here bold. Feature importance is given as the mean (across cross-validation iterations) of median importance of the permutation repetitions.

RF model	Variable	Number of samples	Performance (accuracy/ R^2)	Feature	Importance (mean of medians)
classification	cluster (all)	6620	0.68	PET_SI	1.43
				mean_gwdepth	1.13
				dem	1.08
regression	cluster (regional)	5120	0.79	PET_SI	1.81
				mean_gwdepth	1.25
				dem	1.20
	acf_lag	6620	0.34	mean_gwdepth	1.08
				AI	1.06
				y18_agriculture_10km	1.05
	respt _{SPEI}	6620	0.35	mean_gwdepth	1.20
				AI	1.07
				PET_SI	1.05
	respt _{SPi}	6620	0.35	mean_gwdepth	1.17
				AI	1.05
				y18_artificial_10km	1.05
	acc _{SPEI}	6620	0.35	mean_gwdepth	1.18
				AI	1.07
				P_mm	1.07
	acc _{SPi}	6620	0.39	mean_gwdepth	1.15
				AI	1.06
				y18_artificial_10km	1.05
	acf_lag	5120	0.34	mean_gwdepth	1.08
				AI	1.08
				dem	1.05
	respt_{SPEI}	5120	0.42	mean_gwdepth	1.26
				PET_SI	1.12
				dem	1.05
	respt _{SPi}	5120	0.32	mean_gwdepth	1.17
				PET_SI	1.06
				AI	1.04
	acc_{SPEI}	5120	0.41	mean_gwdepth	1.23
				PET_SI	1.12
				dem	1.06
	acc _{SPi}	5120	0.35	mean_gwdepth	1.16
				PET_SI	1.07
				AI	10.5
	resid_sen_{SPEI}	6620	0.42	PET_mm	1.11
				y18_artificial_10km	1.09
				PET_SI	1.06
	resid_sen_{SPi}	6620	0.41	PET_mm	1.09
				y18_artificial_10km	1.08
				PET_SI	1.07