

S1 Spring-specific model performance and catchment characteristics

S1.1 Nival cluster

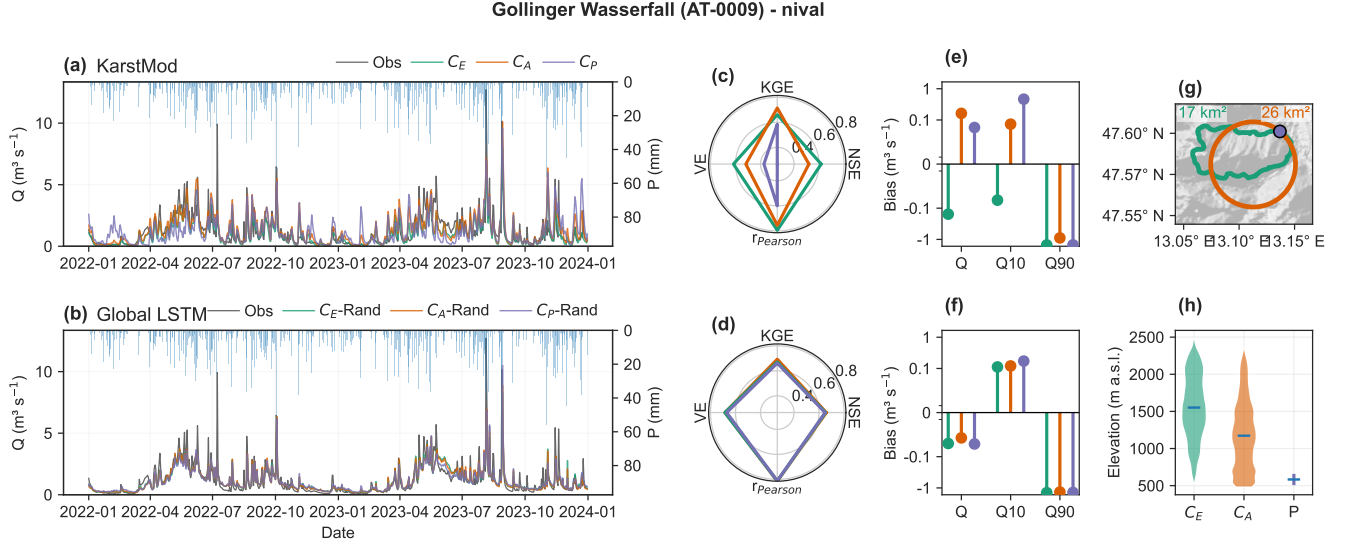


Figure S1. Detailed model performance for Gollinger Wasserfall (AT-0009). The first panel of each pair shows KarstMod and the second the global LSTM. (a, b) Hydrographs of observed and simulated discharge during the test period for the different catchment representations. (c, d) Spider plots of KGE, NSE, Pearson correlation (r), and volumetric efficiency (VE). Values below zero are not visualised. For visualization, metric values below zero are truncated at zero. (e, f) Bias for low flow (Q10, 10th percentile), high flow (Q90, 90th percentile), and overall flow (Q), shown on a symmetric logarithmic y-axis. (g) Map showing the delineated catchment boundaries for all three catchment representations (C_E , C_A , C_P), with hillshade derived from the Copernicus DEM GLO-30 (ESA, 2022). The expert-based catchment delineation (C_E) is taken from the ALPAKAS dataset (Joger et al., 2026). (h) Elevation distributions of C_E , C_A , and C_P , shown as violin plots.

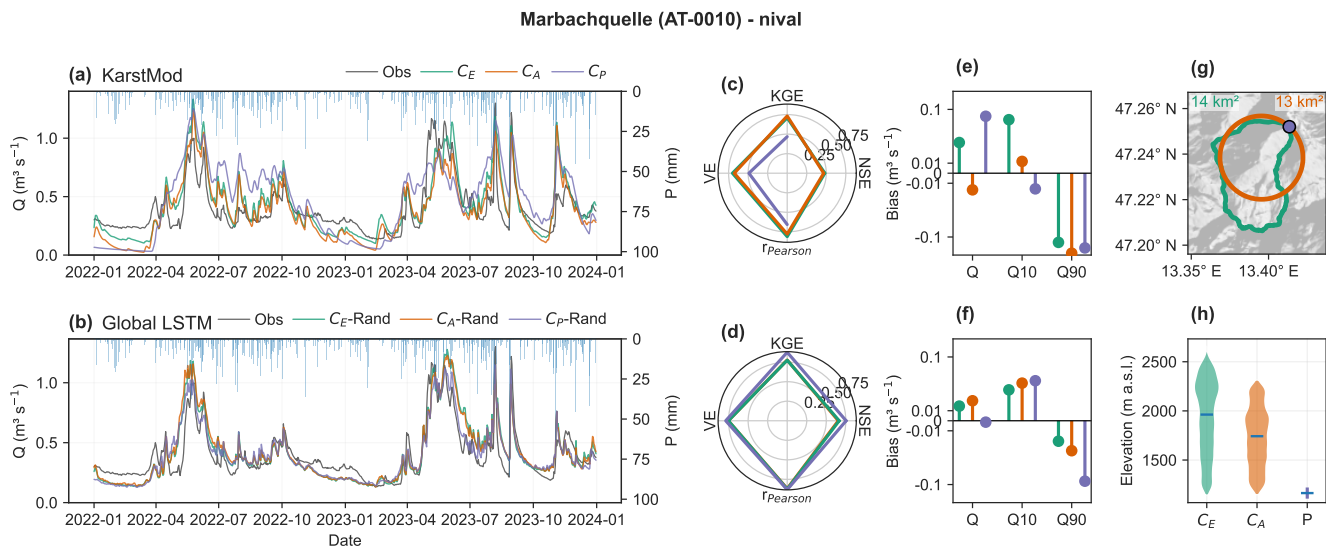


Figure S2. Detailed model performance for Marbachquelle (AT-0010).

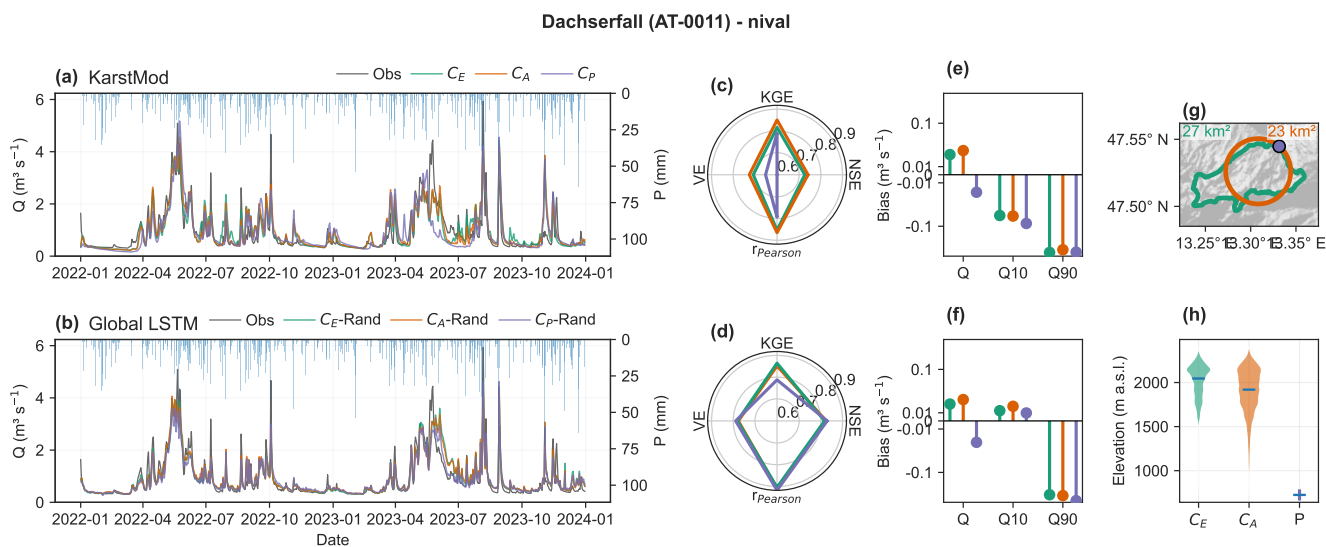


Figure S3. Detailed model performance for Dachserfall (AT-0011).

Schwarze Torrenquelle (AT-0012) - nival

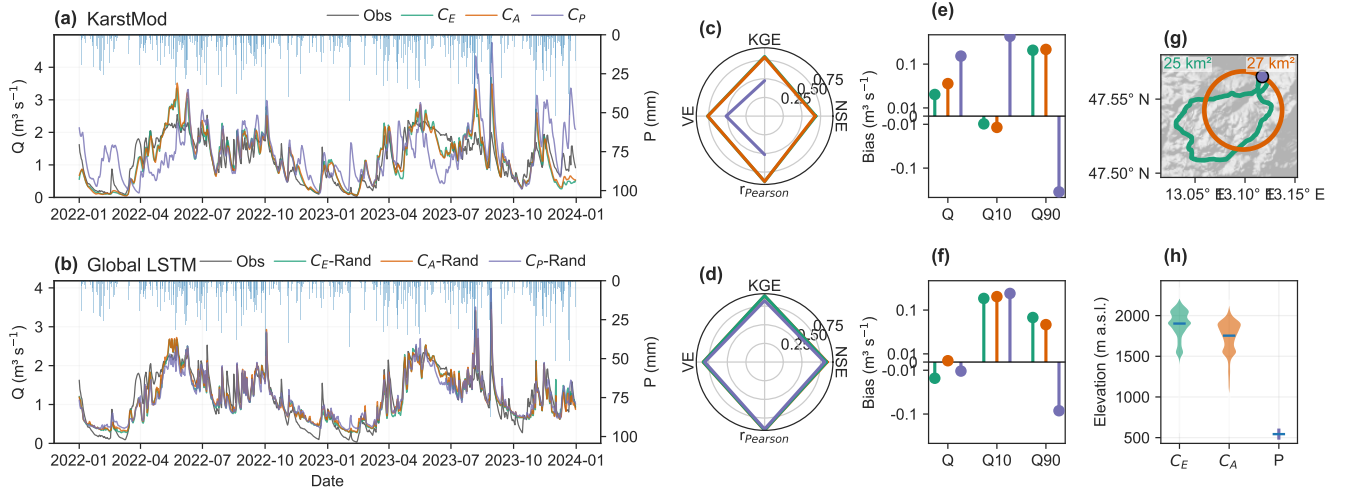


Figure S4. Detailed model performance for Schwarze Torrenquelle (AT-0012).

Schwarzlackenquelle (AT-0013) - nival

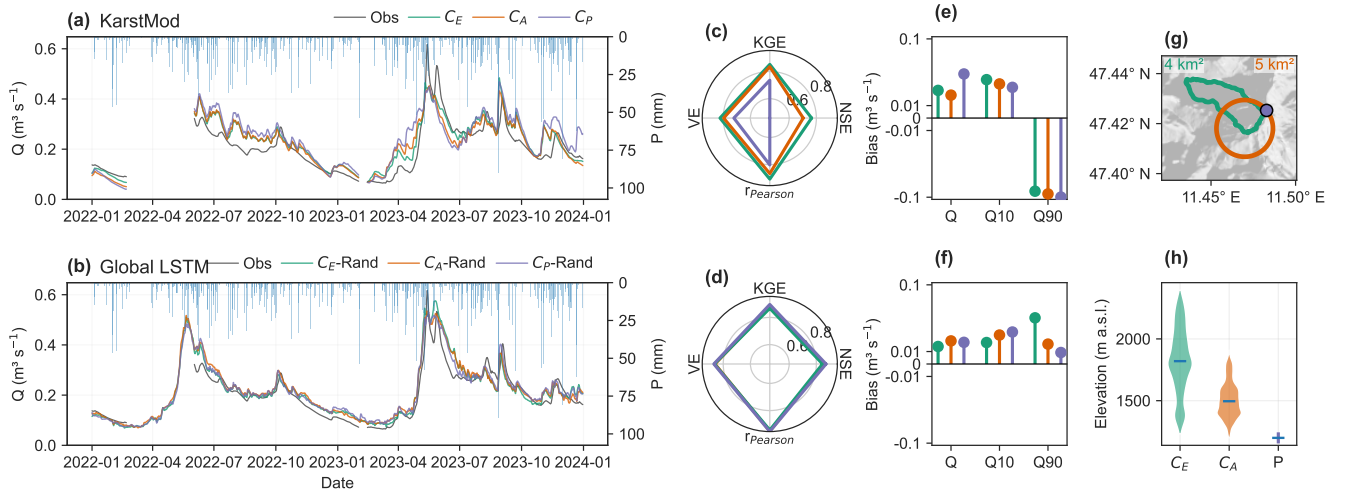


Figure S5. Detailed model performance for Schwarzlackenquelle (AT-0013).

Schreiende Brunnen (AT-0014) - nival

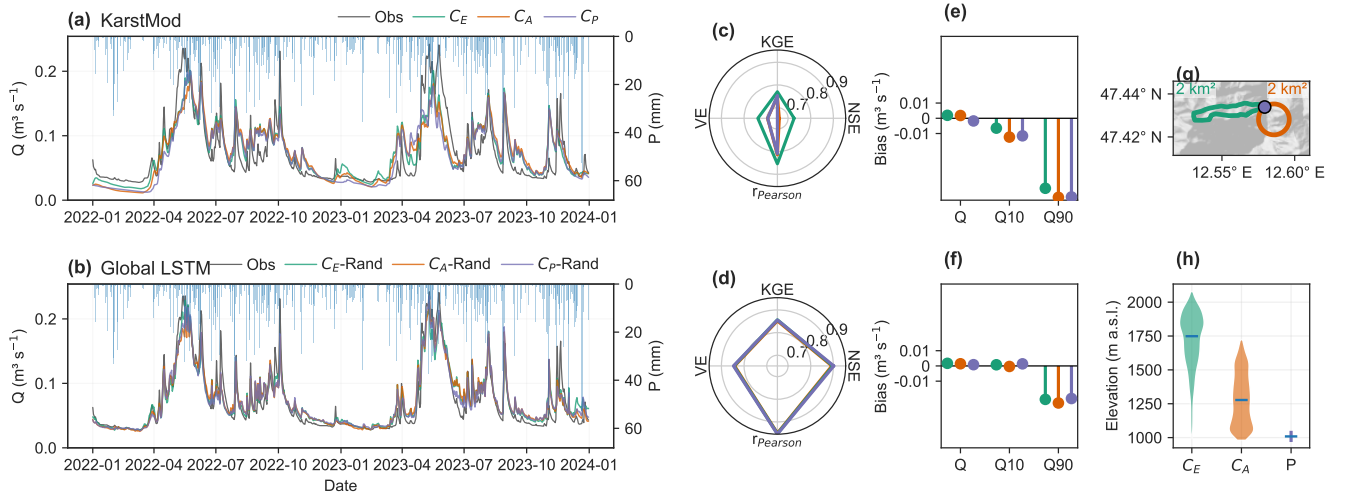


Figure S6. Detailed model performance for Schreiende Brunnen (AT-0014).

Ursprungquelle (Lehnberg) (AT-0024) - nival

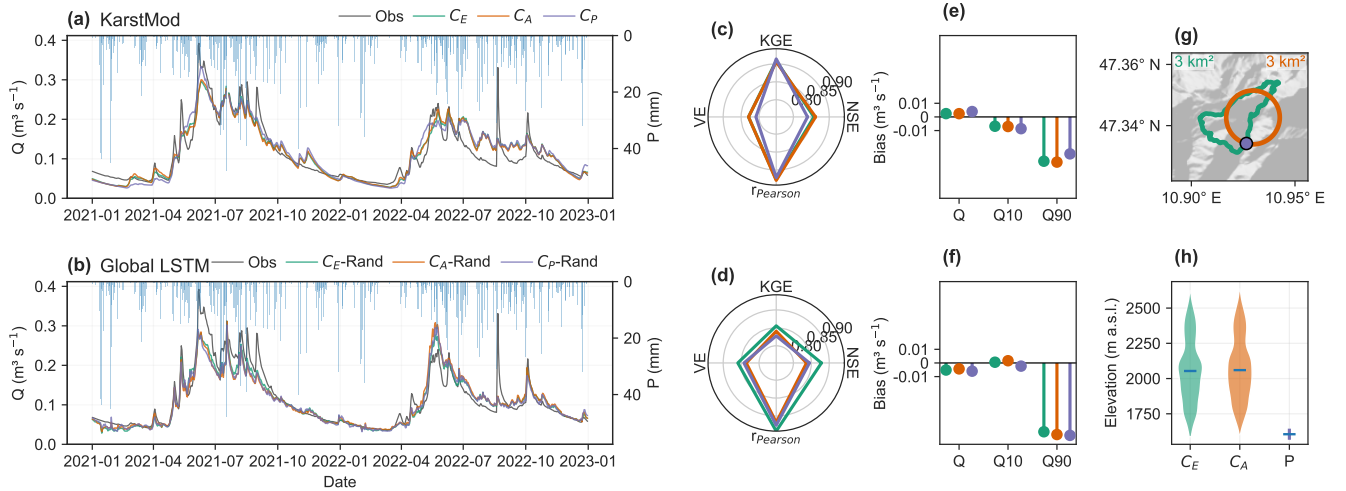


Figure S7. Detailed model performance for Ursprungquelle (Lehnberg) (AT-0024).

Siebenbrunnenquelle (AT-0025) - nival

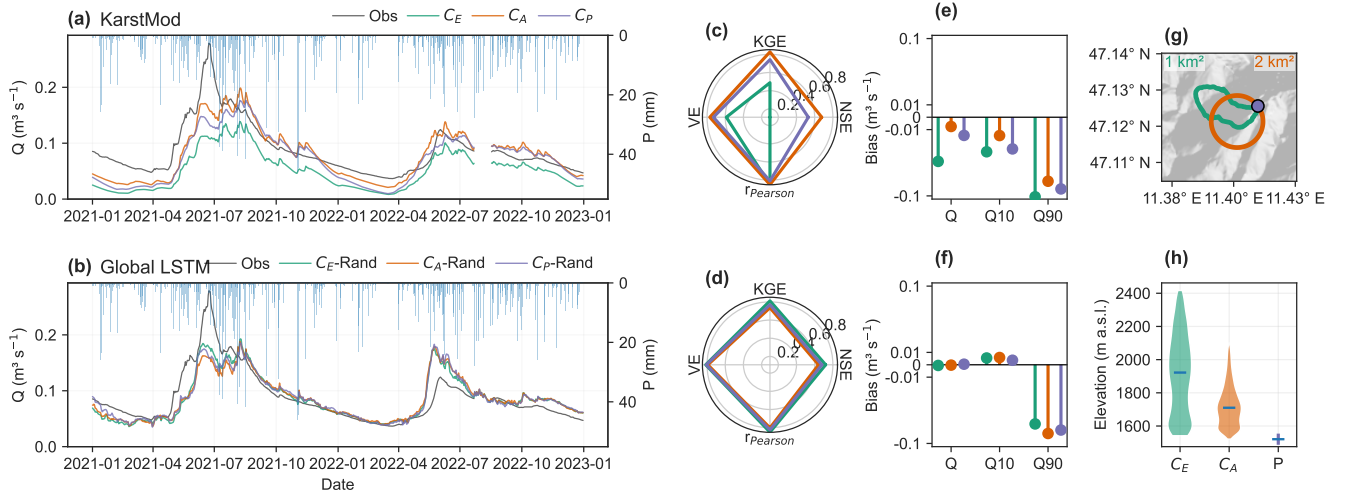


Figure S8. Detailed model performance for Siebenbrunnenquelle (AT-0025).

Gerstenbödenquelle (AT-0035) - nival

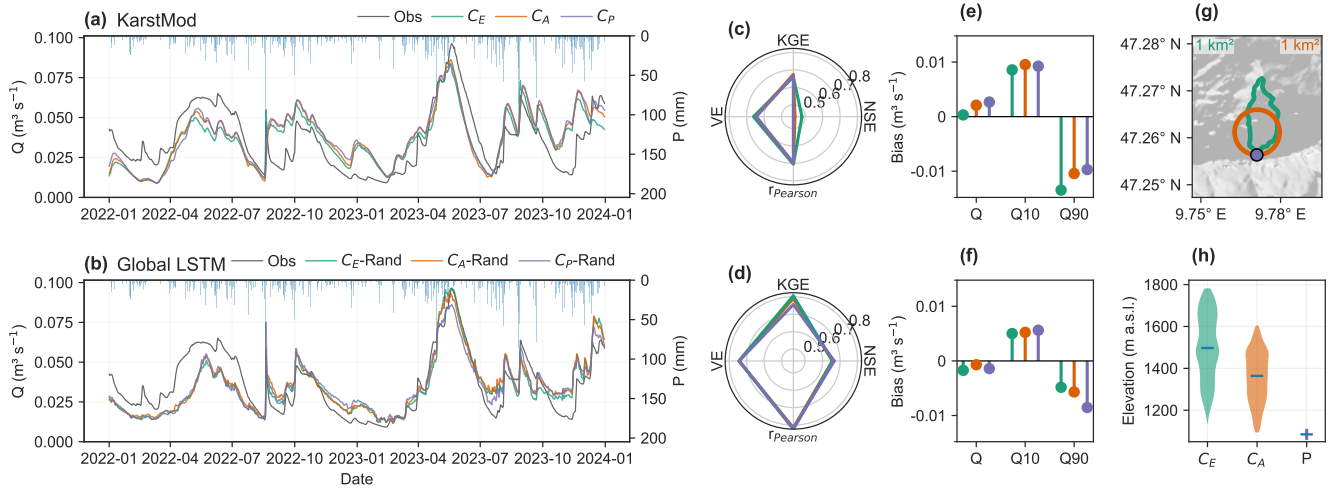


Figure S9. Detailed model performance for Gerstenbödenquelle (AT-0035).

Fidelisque (AT-0037) - nival

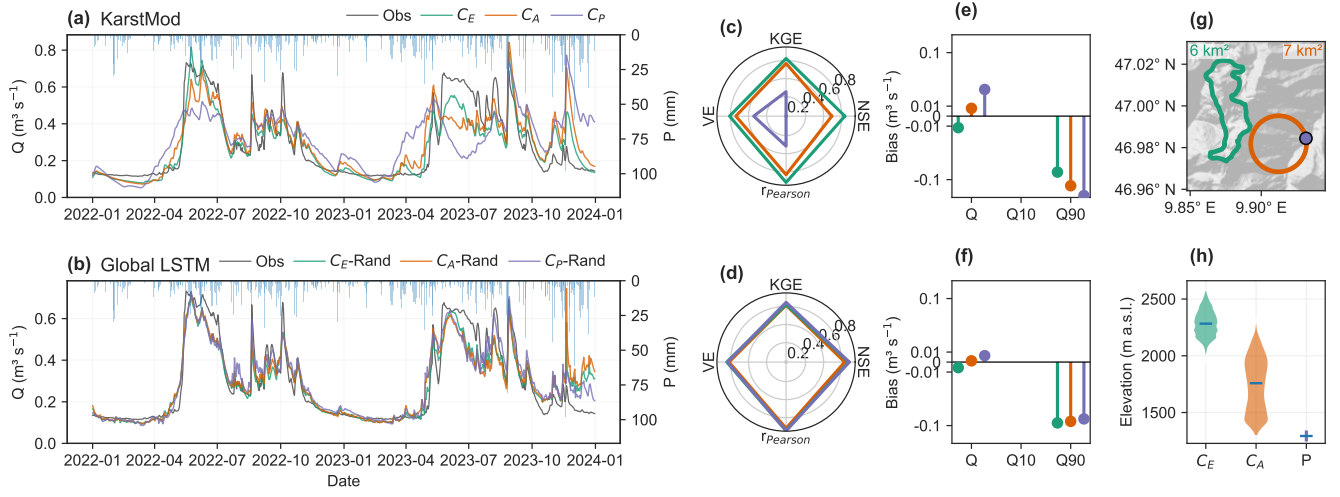


Figure S10. Detailed model performance for Fidelisque (AT-0037).

Aubachquelle (AT-0038) - nival

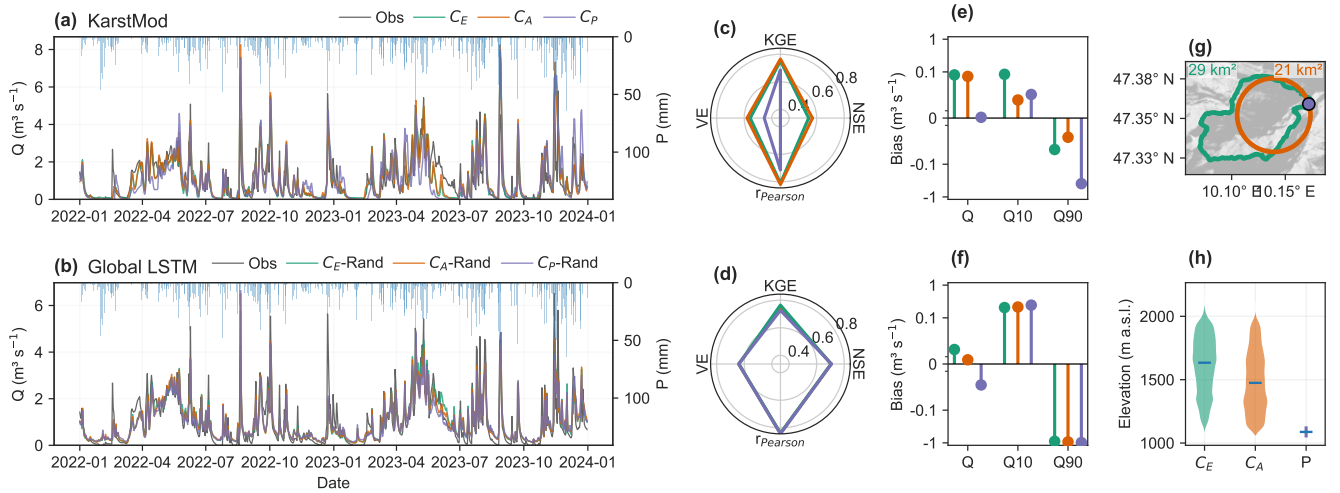


Figure S11. Detailed model performance for Aubachquelle (AT-0038).

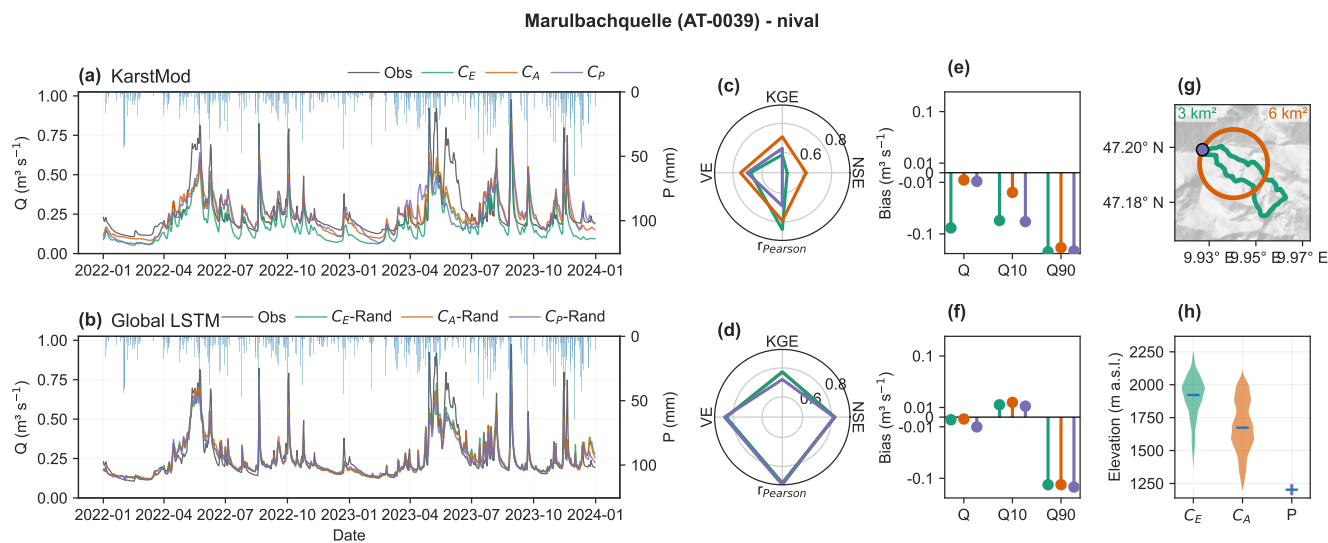


Figure S12. Detailed model performance for Marulbachquelle (AT-0039).

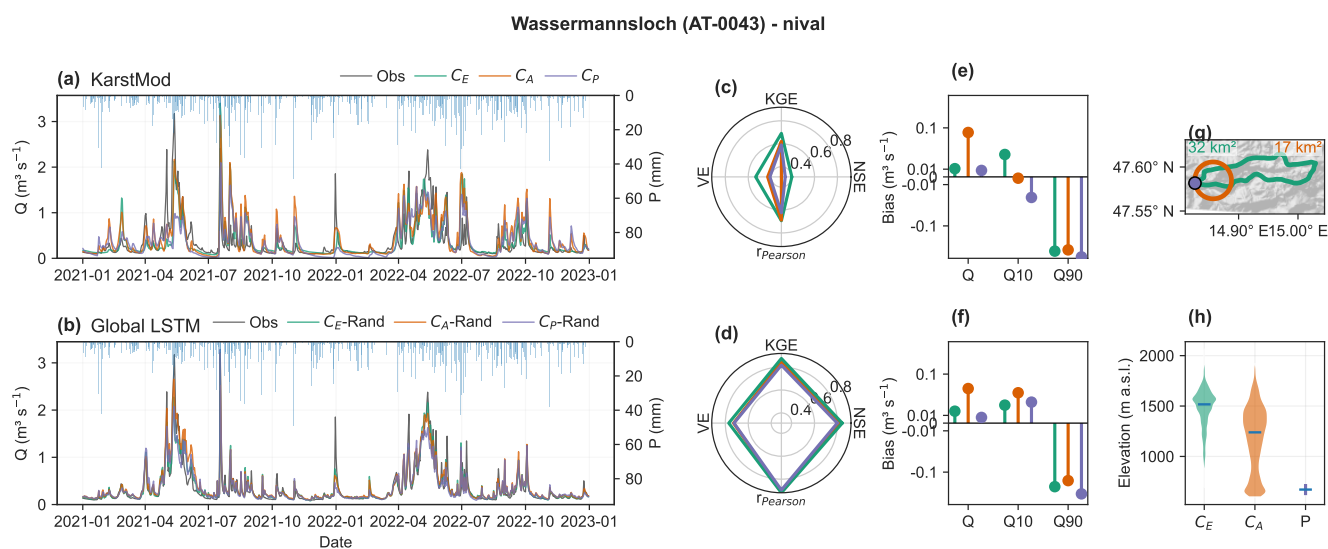


Figure S13. Detailed model performance for Wassermannsloch (AT-0043).

Eibachquelle (AT-0055) - nival

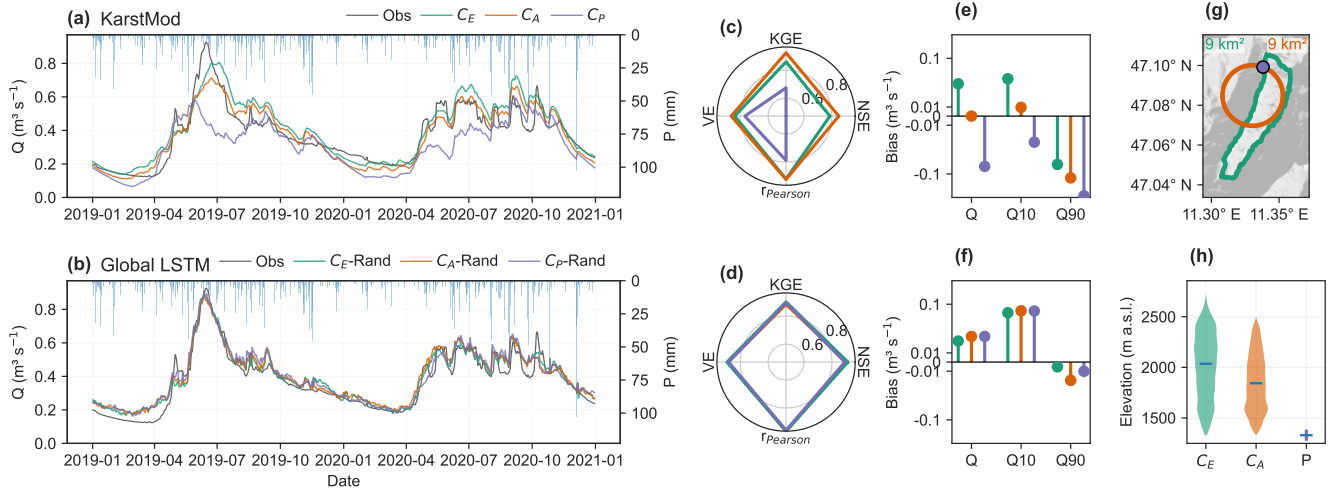


Figure S14. Detailed model performance for Eibachquelle (AT-0055).

Obwaldquelle (AT-0060) - nival

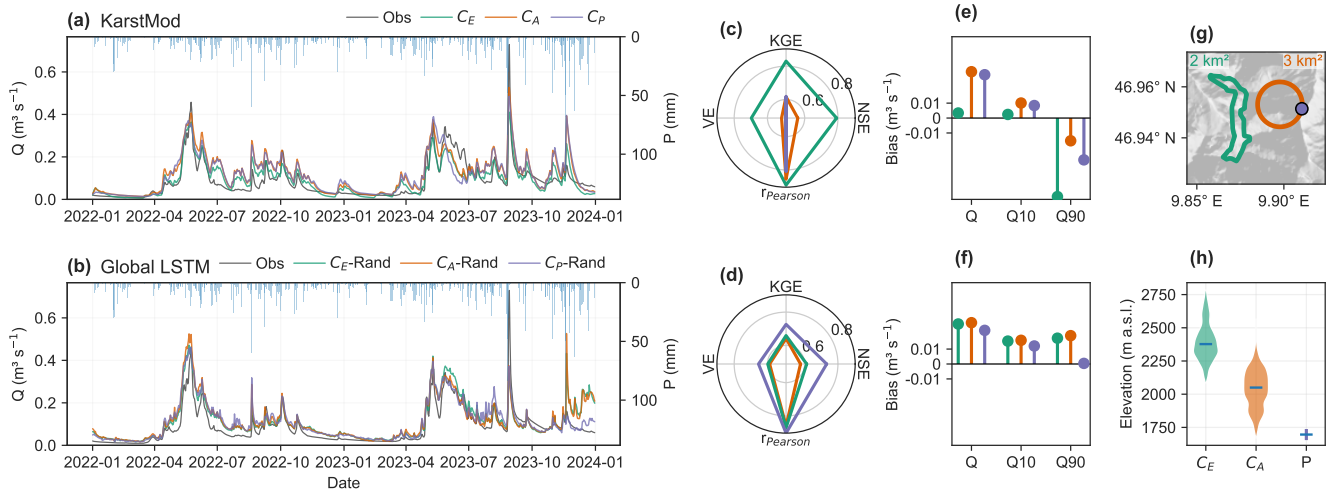


Figure S15. Detailed model performance for Obwaldquelle (AT-0060).

Schlichenden Brünnen (CH-0005) - nival

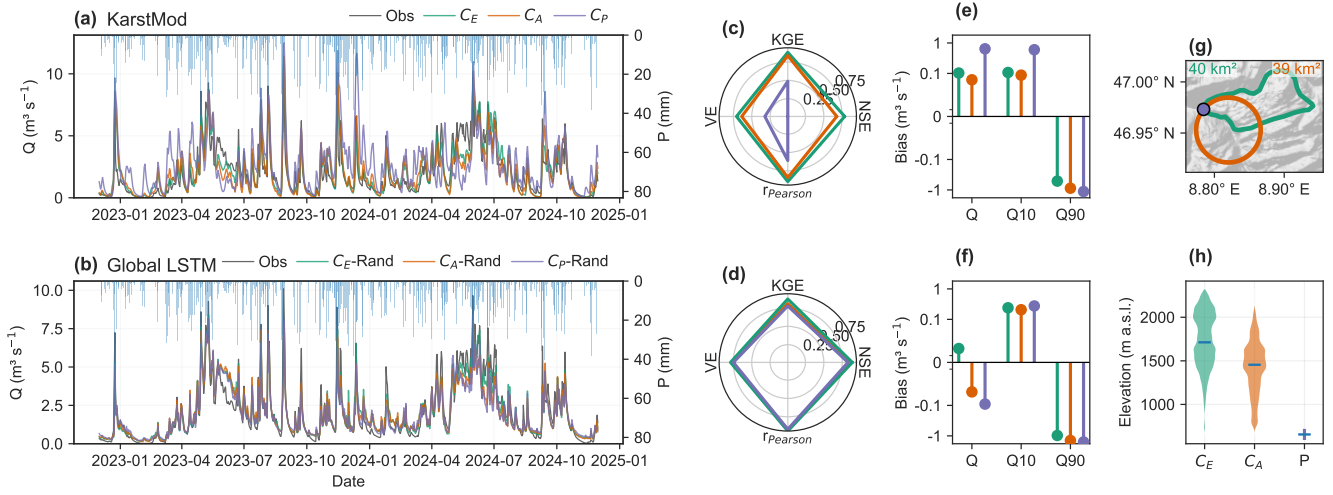


Figure S16. Detailed model performance for Schlichenden Brünnen (CH-0005).

S1.2 Nivo-pluvial cluster

Teufelskirche (AT-0001) - nivo-pluvial

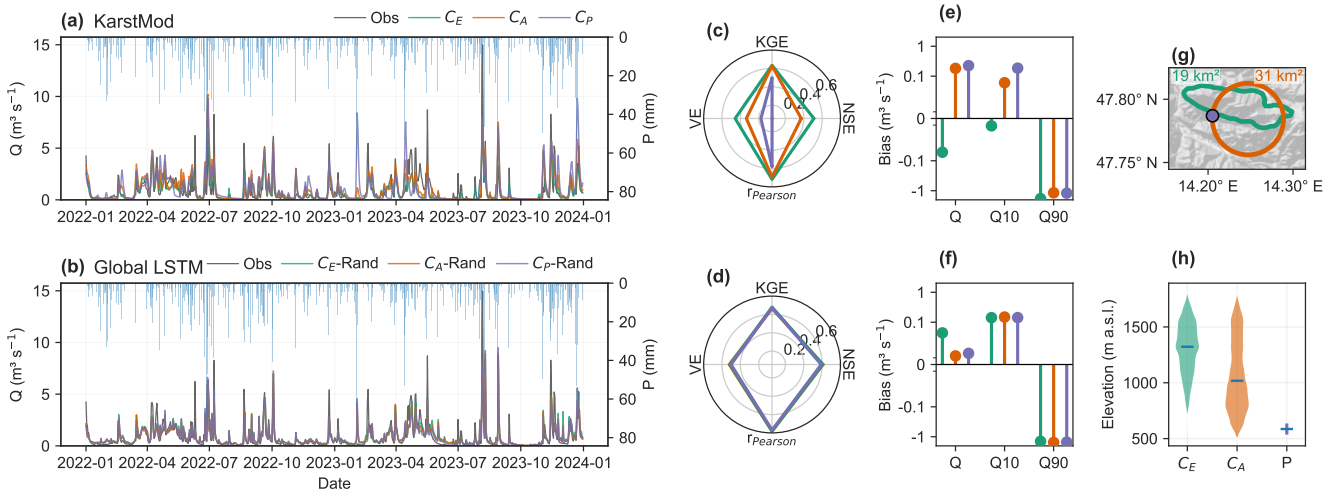


Figure S17. Detailed model performance for Teufelskirche (AT-0001).

Steyernquelle (AT-0004) - nivo-pluvial

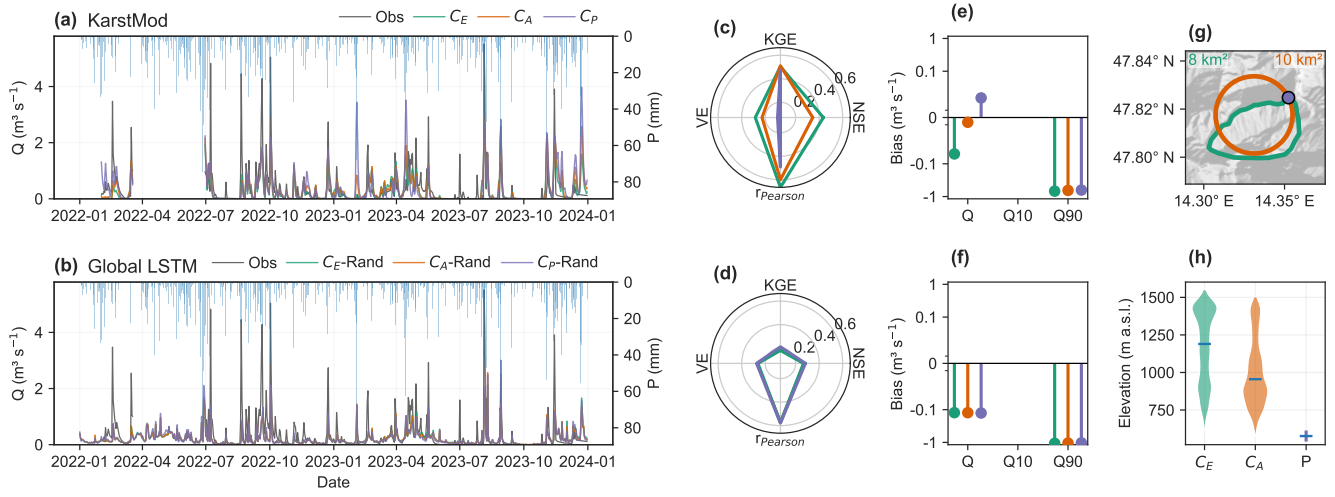


Figure S18. Detailed model performance for Steyernquelle (AT-0004).

Rettenbachquelle (AT-0006) - nivo-pluvial

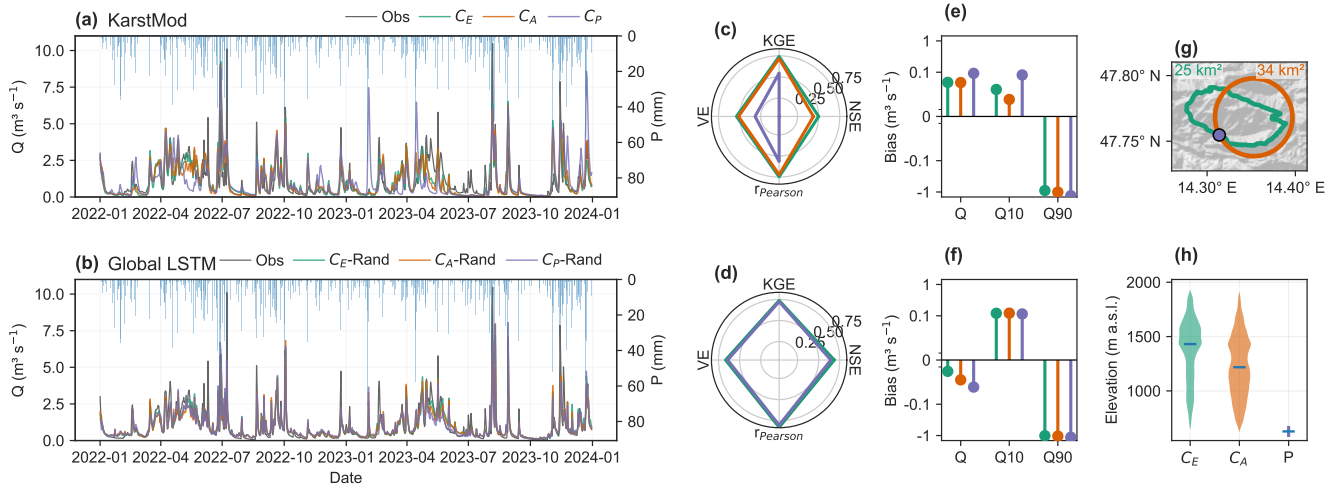


Figure S19. Detailed model performance for Rettenbachquelle (AT-0006).

Quelle Brunnental (AT-0007) - nivo-pluvial

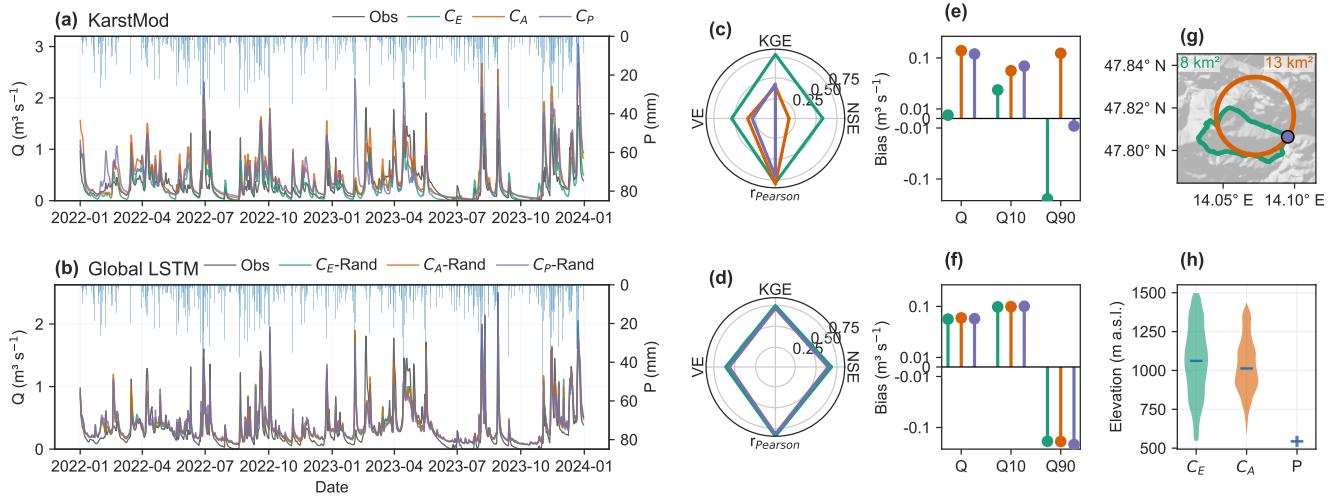


Figure S20. Detailed model performance for Quelle Brunnental (AT-0007).

Miesenbachursprung (AT-0008) - nivo-pluvial

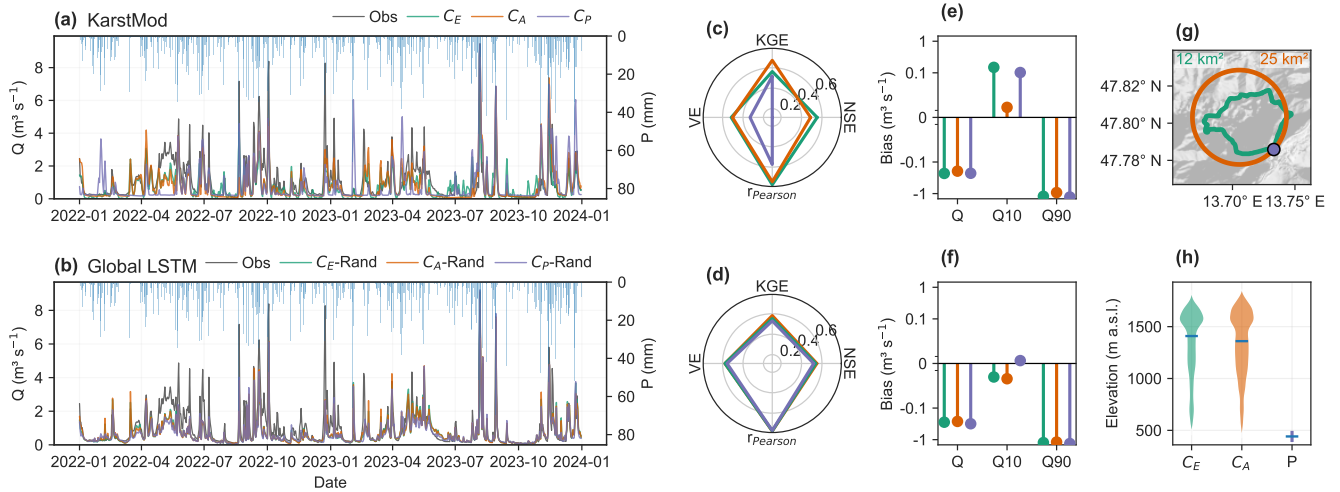


Figure S21. Detailed model performance for Miesenbachursprung (AT-0008).

Pulverermühlquelle (AT-0021) - nivo-pluvial

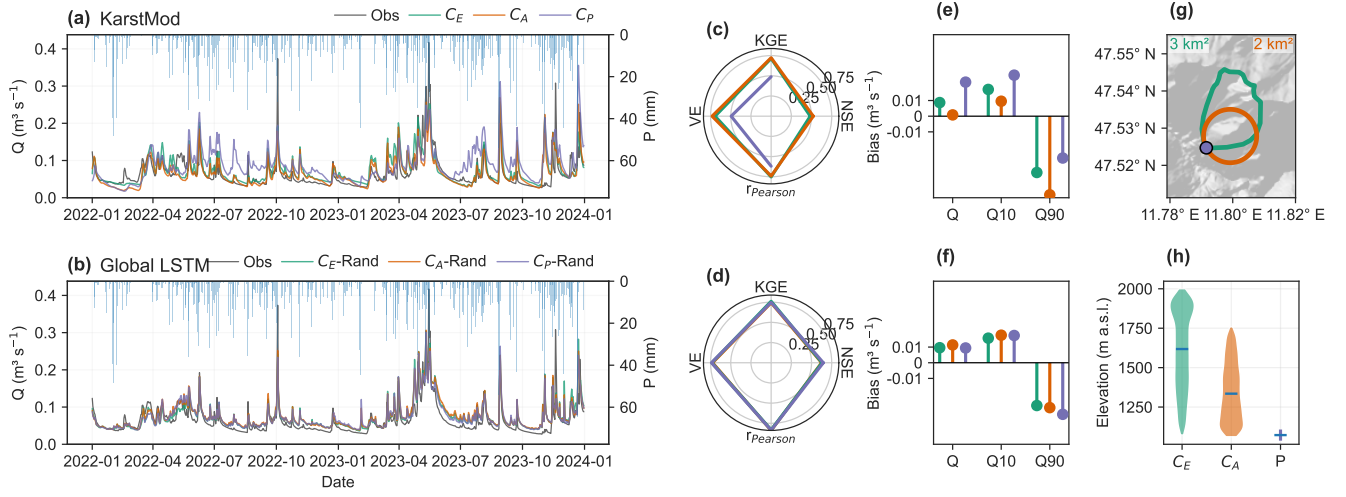


Figure S22. Detailed model performance for Pulverermühlquelle (AT-0021).

Auebachquelle (AT-0022) - nivo-pluvial

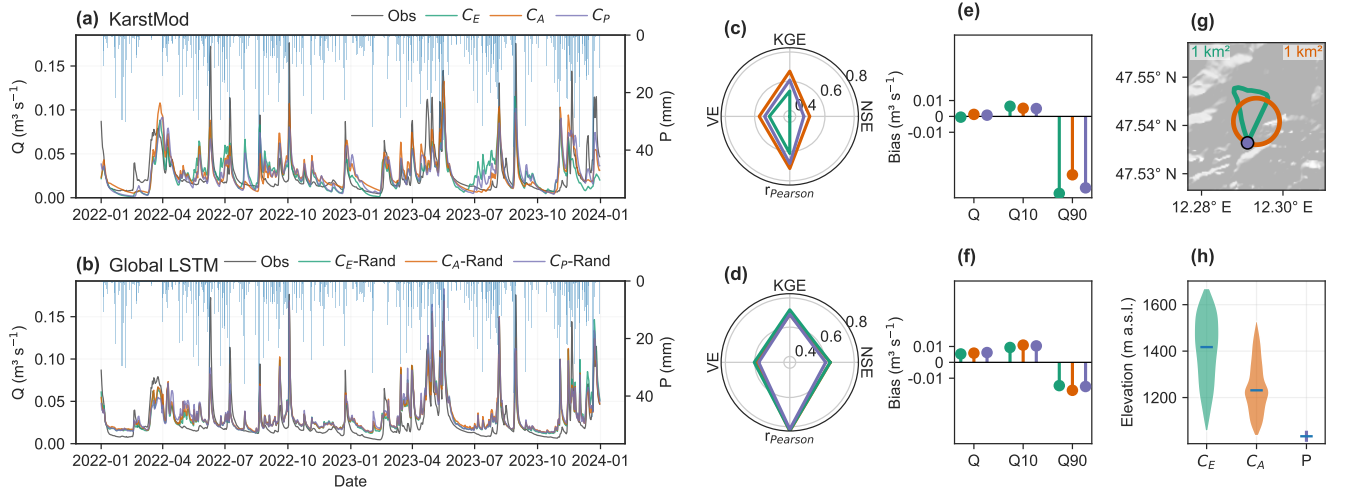


Figure S23. Detailed model performance for Auebachquelle (AT-0022).

Lastal-Stollenquelle (AT-0026) - nivo-pluvial

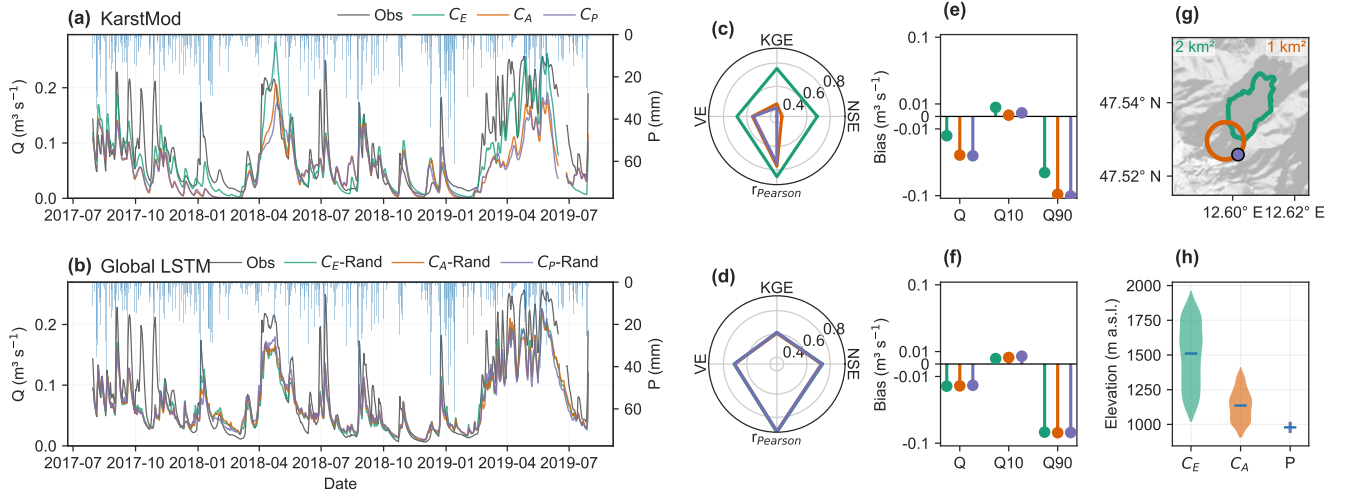


Figure S24. Detailed model performance for Lastal-Stollenquelle (AT-0026).

Große Mühlquelle (AT-0027) - nivo-pluvial

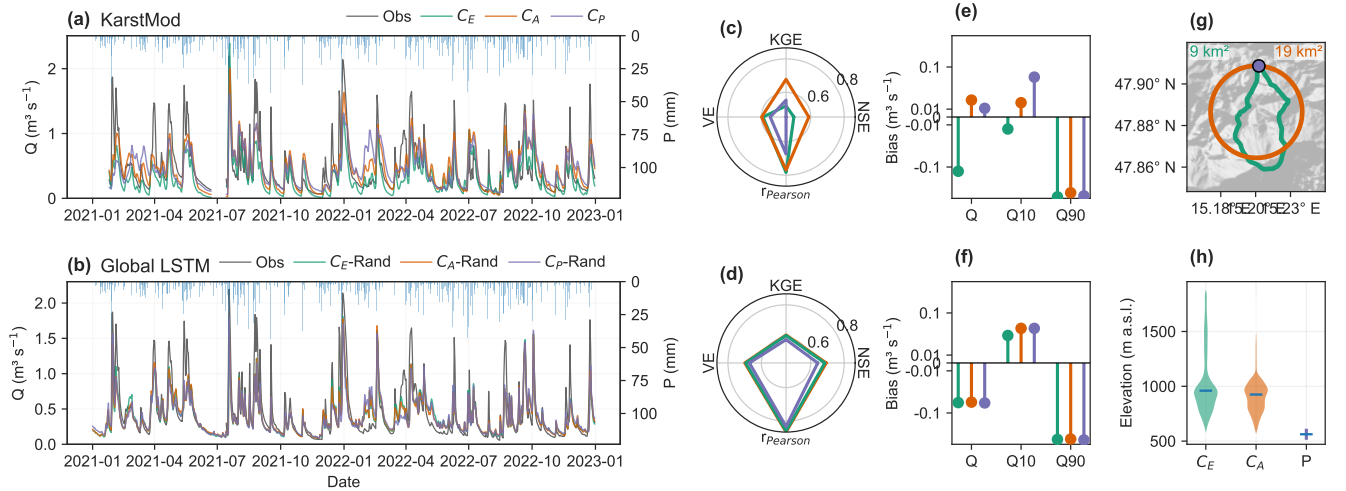


Figure S25. Detailed model performance for Große Mühlquelle (AT-0027).

Reithbachquelle (AT-0029) - nivo-pluvial

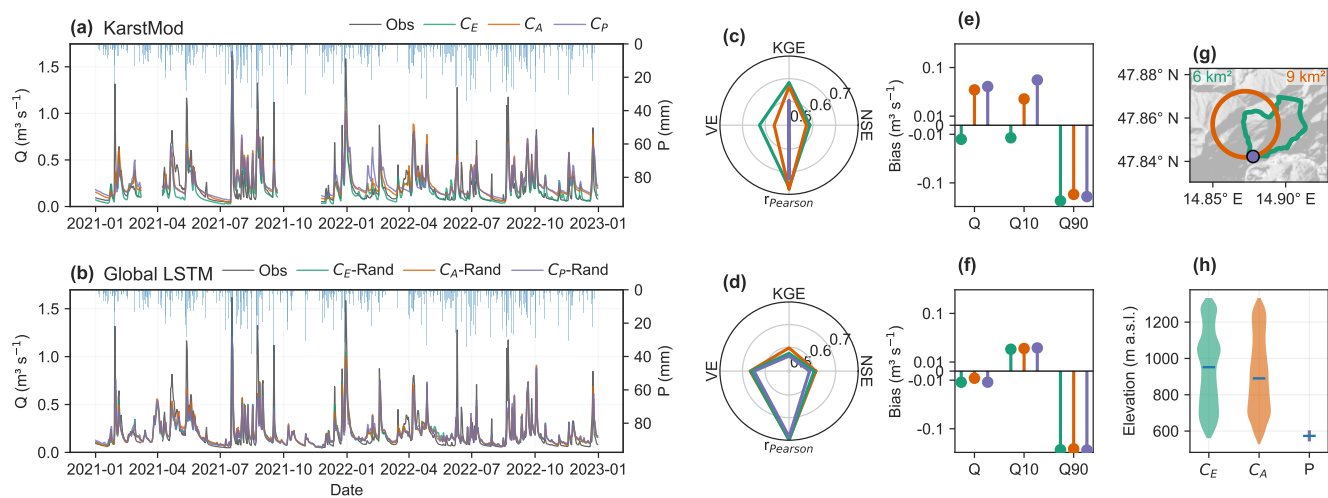


Figure S26. Detailed model performance for Reithbachquelle (AT-0029).

Steinbachquelle (AT-0030) - nivo-pluvial

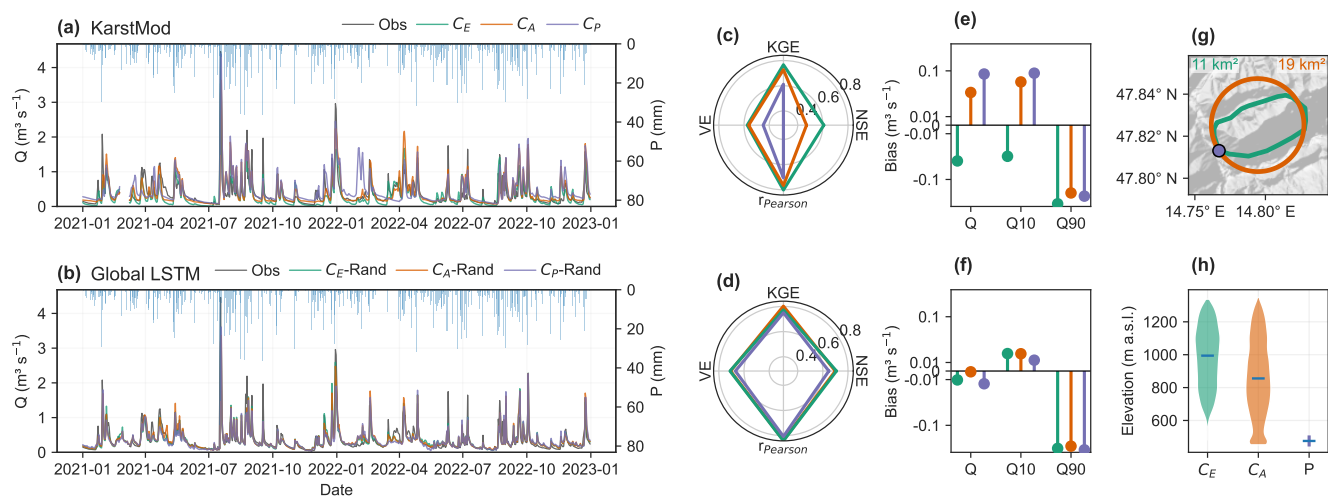


Figure S27. Detailed model performance for Steinbachquelle (AT-0030).

Roßlochquelle (AT-0040) - nivo-pluvial

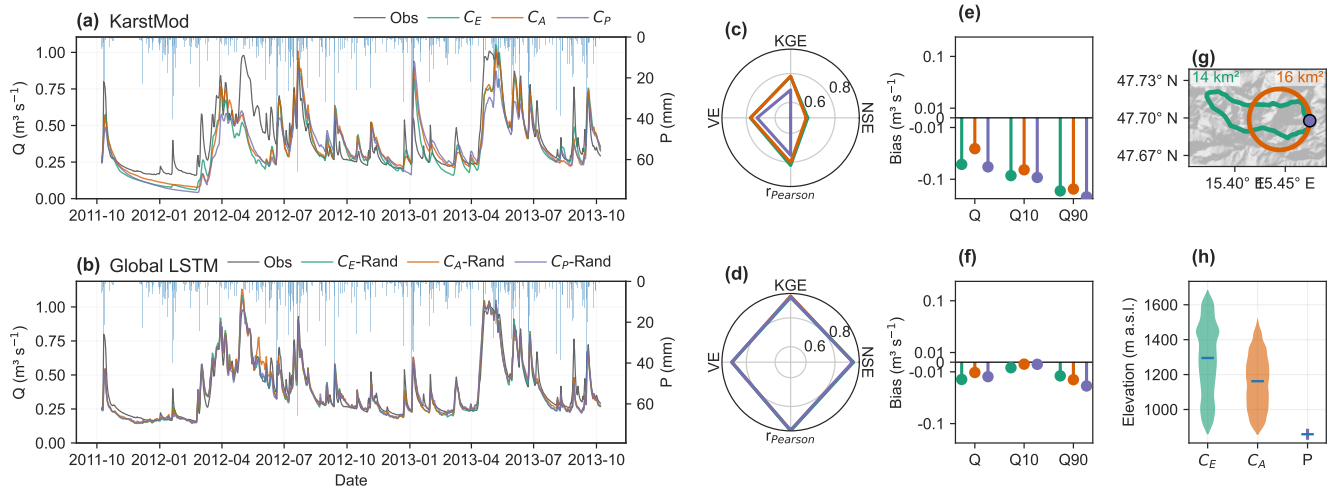


Figure S28. Detailed model performance for Roßlochquelle (AT-0040).

Schwabeltalquelle (AT-0046) - nivo-pluvial

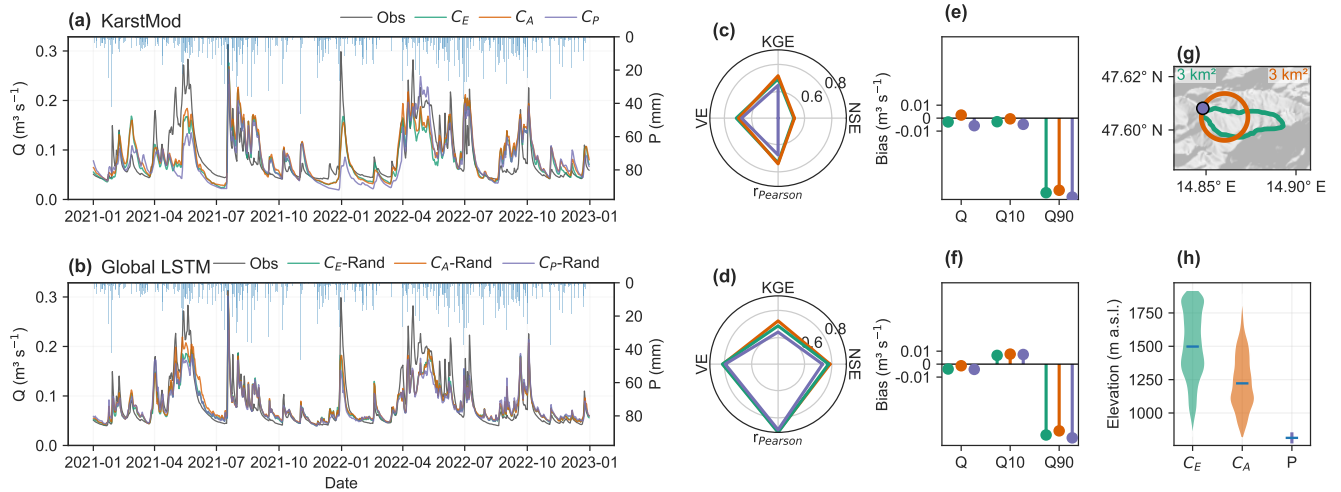


Figure S29. Detailed model performance for Schwabeltalquelle (AT-0046).

Etzbachquelle (AT-0063) - nivo-pluvial

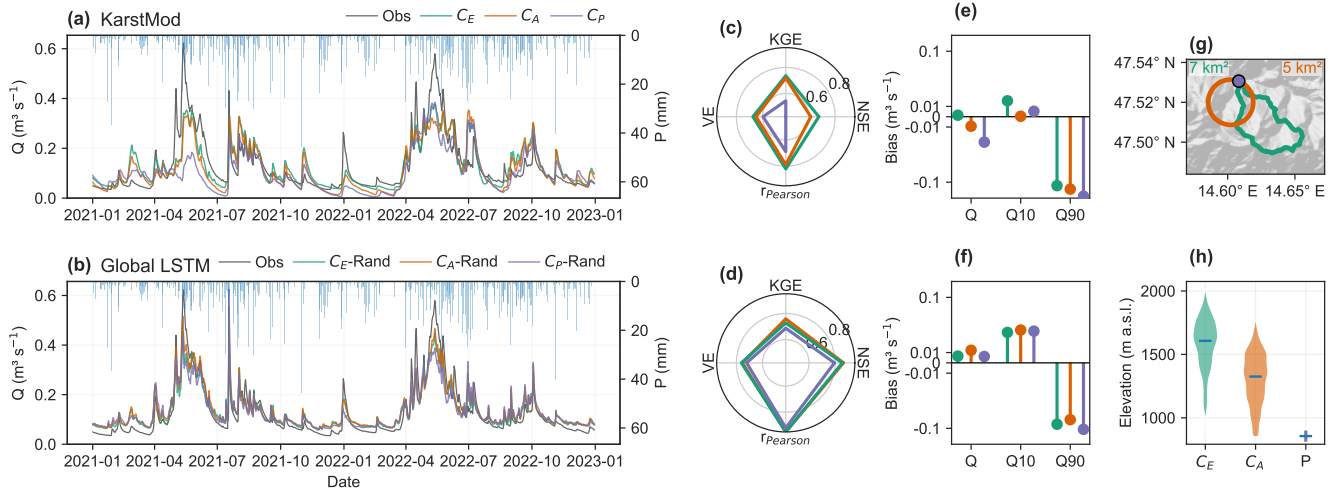


Figure S30. Detailed model performance for Etzbachquelle (AT-0063).

S1.3 Pluvial cluster

Source de la Birse (CH-0001) - pluvial

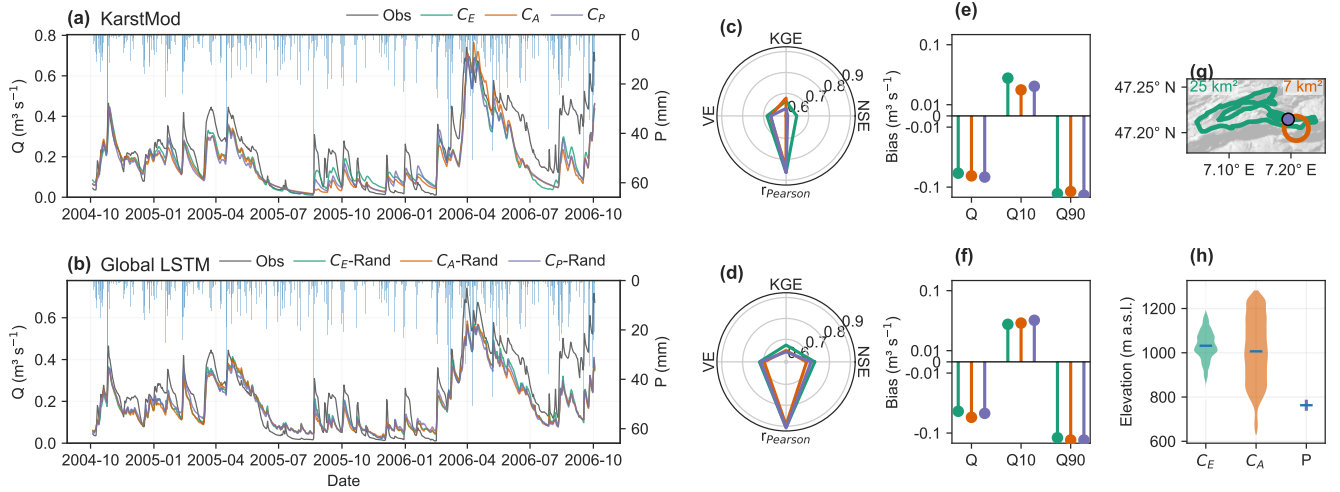


Figure S31. Detailed model performance for Source de la Birse (CH-0001).

Source de l'Areuse (CH-0004) - pluvial

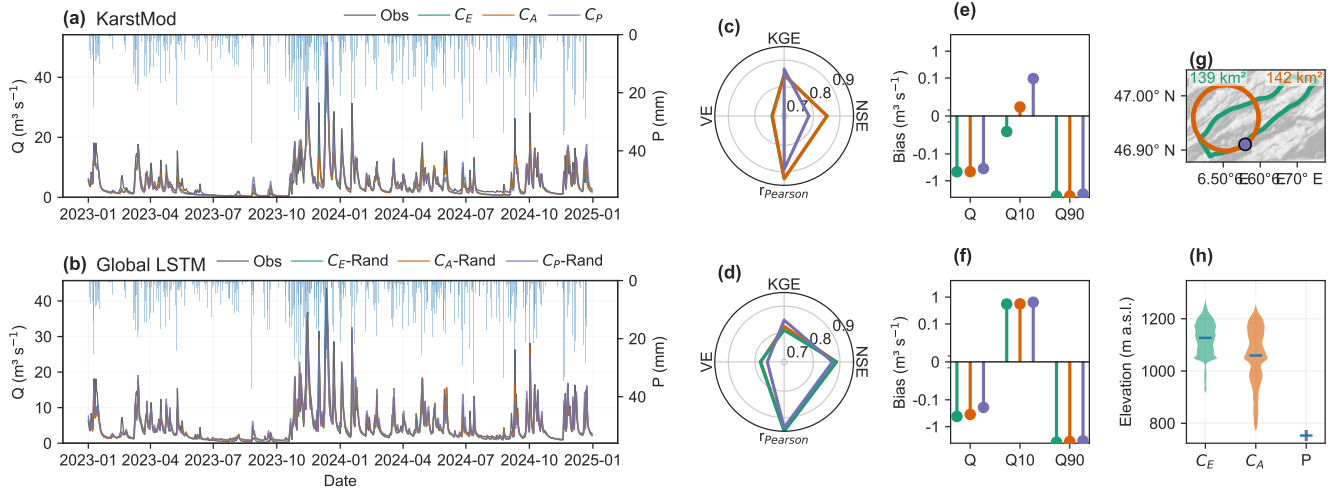


Figure S32. Detailed model performance for Source de l'Areuse (CH-0004).

Source de la Lionne (CH-0008) - pluvial

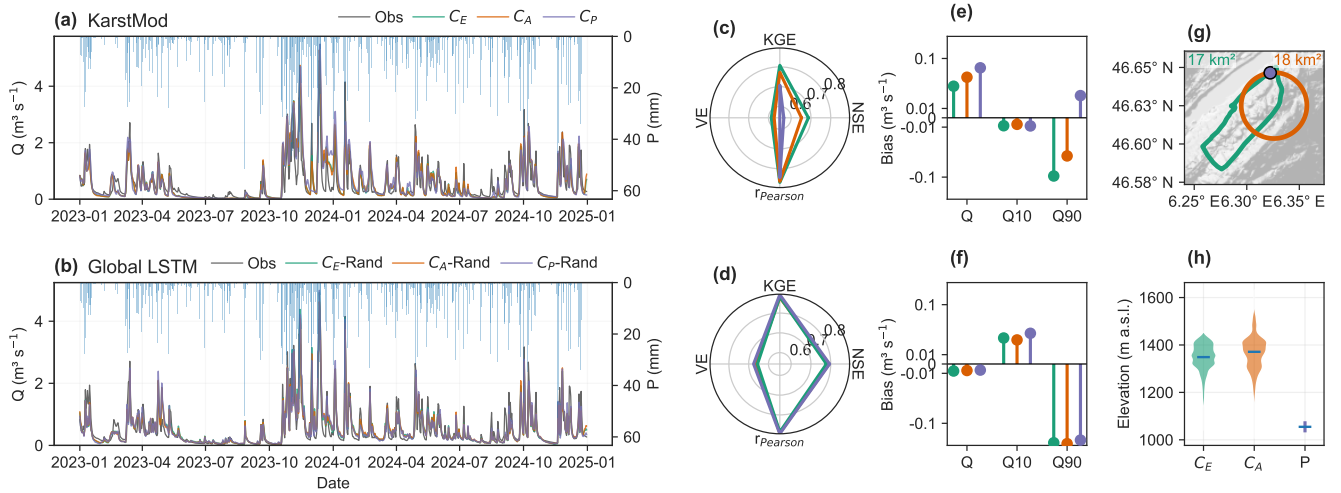


Figure S33. Detailed model performance for Source de la Lionne (CH-0008).

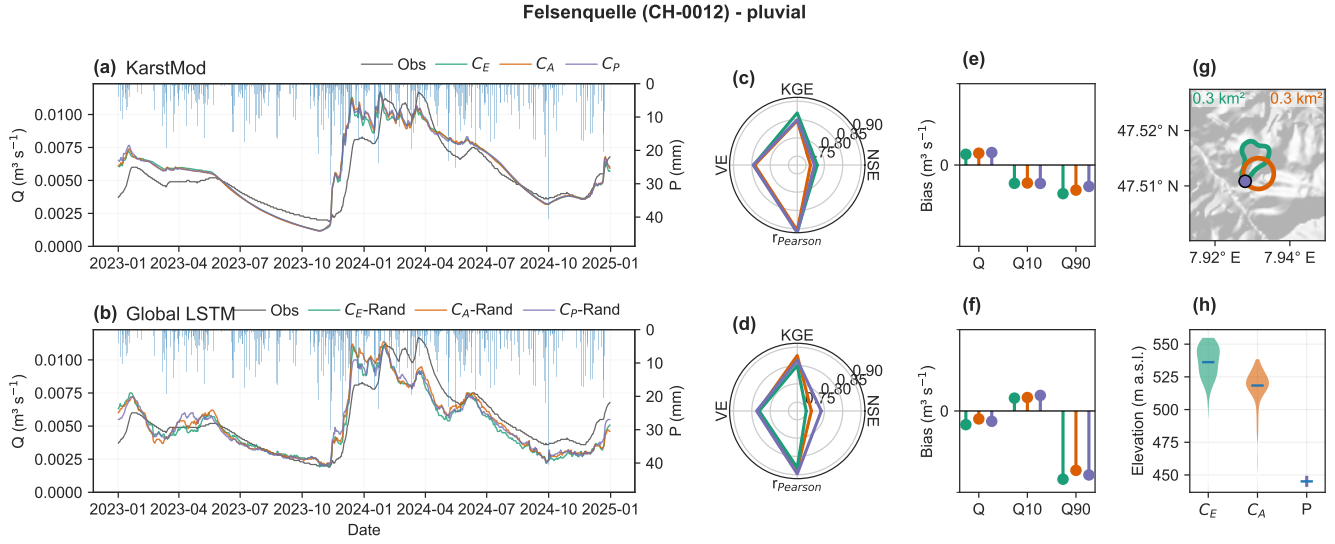


Figure S34. Detailed model performance for Felsenquelle (CH-0012).

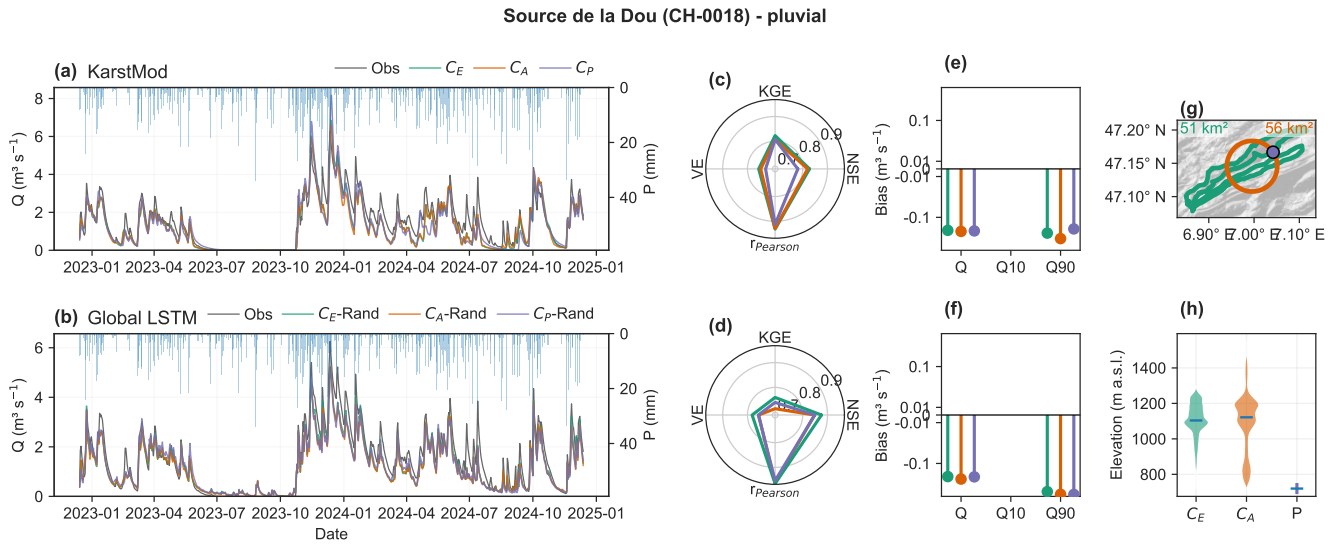


Figure S35. Detailed model performance for Source de la Dou (CH-0018).

Milandre karst system (CH-0026) - pluvial

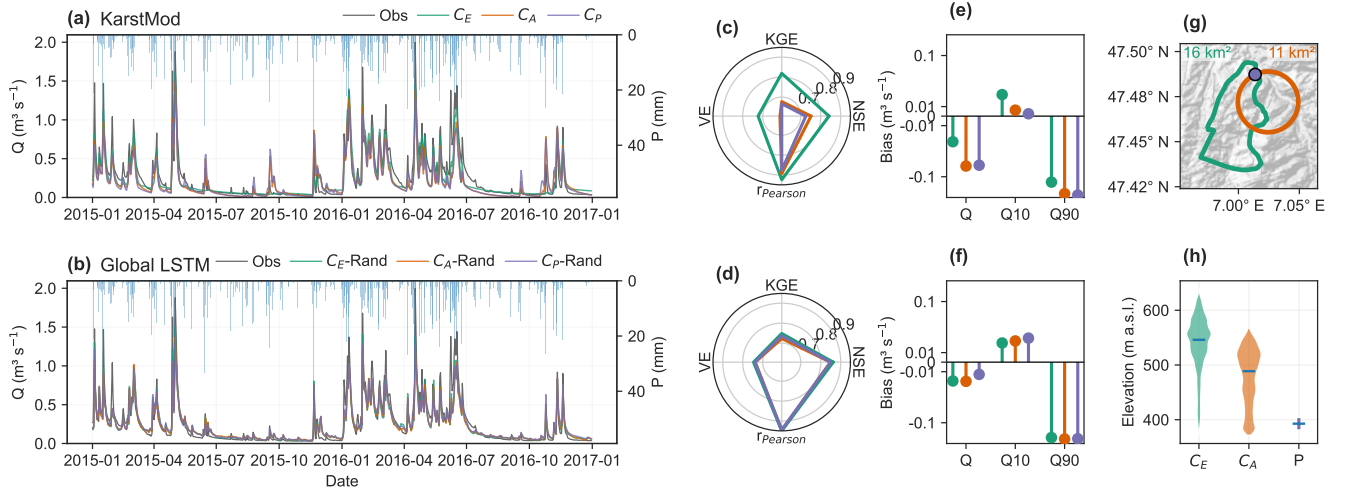


Figure S36. Detailed model performance for Milandre karst system (CH-0026).

Blautopf (DE-0015) - pluvial

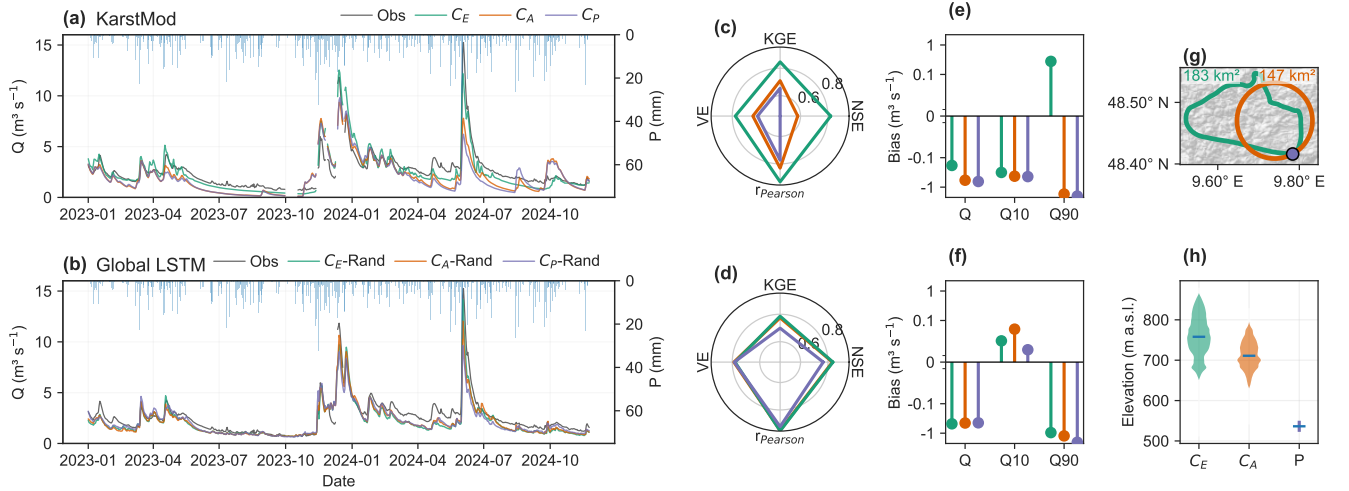


Figure S37. Detailed model performance for Blautopf (DE-0015).

Source d'Arcier (FR-0007) - pluvial

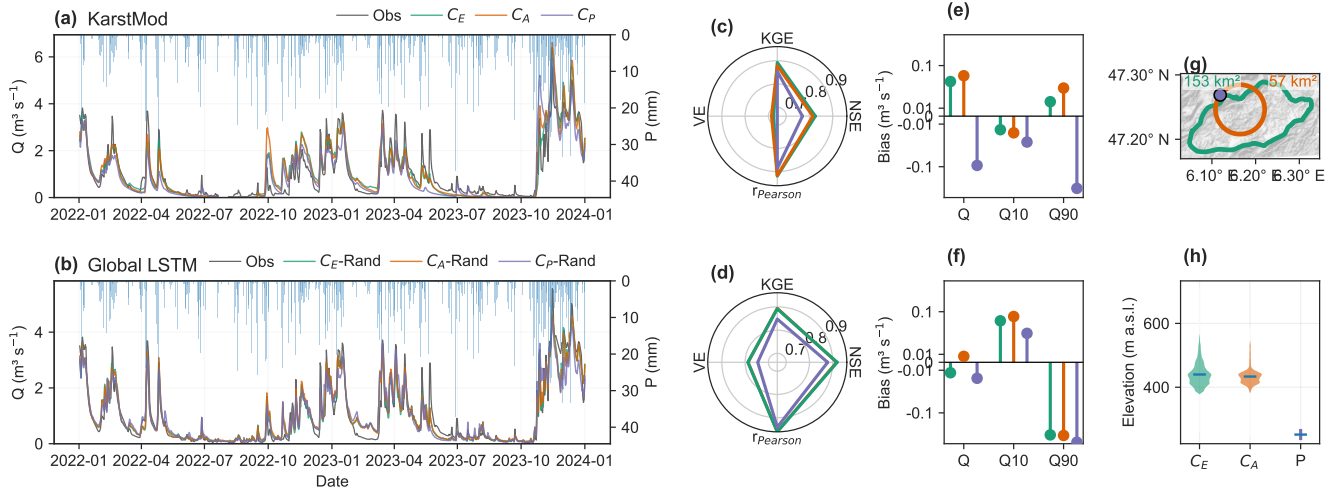


Figure S38. Detailed model performance for Source d'Arcier (FR-0007).

Source du Lison (FR-0011) - pluvial

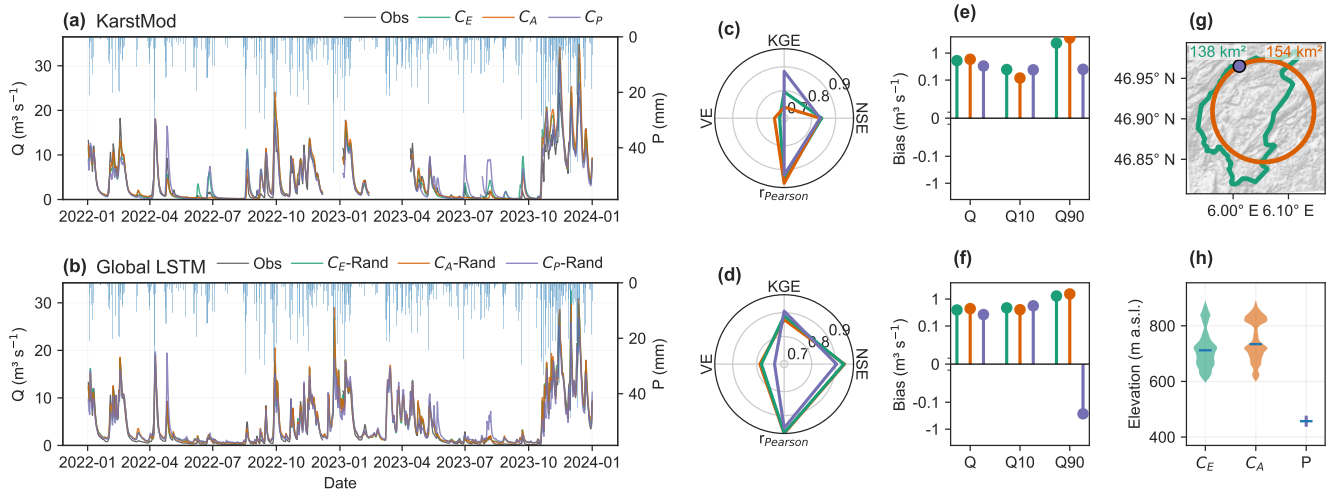


Figure S39. Detailed model performance for Source du Lison (FR-0011). Expert-based catchment delineation (C_E): Charlier et al. (2014).

Source du Verneau (FR-0013) - pluvial

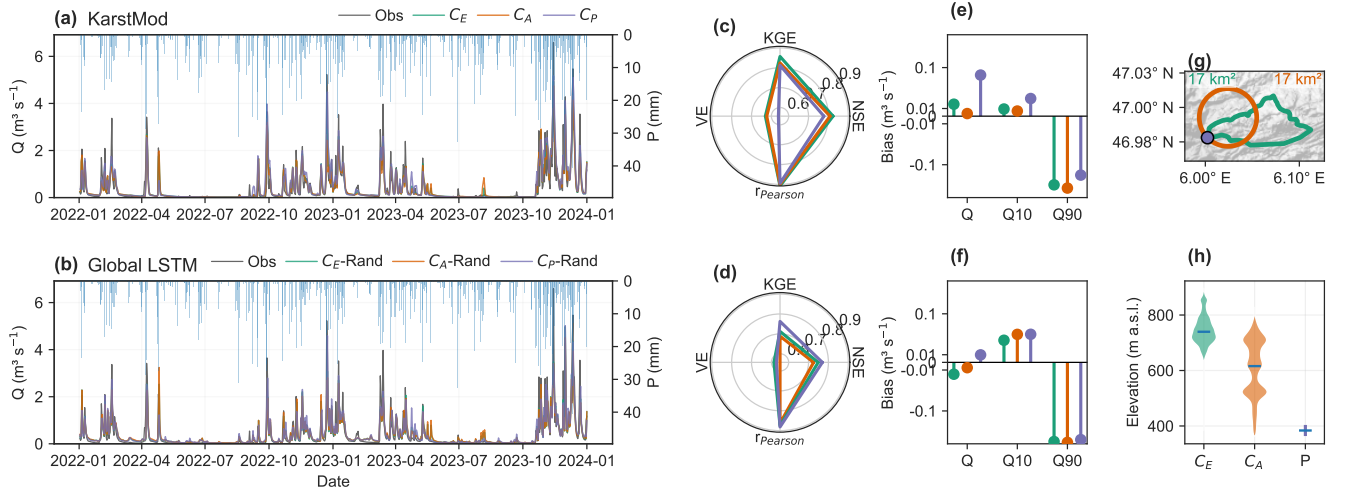


Figure S40. Detailed model performance for Source du Verneau (FR-0013). Expert-based catchment delineation (C_E): Charlier et al. (2014).

Source de la Sorgue (FR-0024) - pluvial

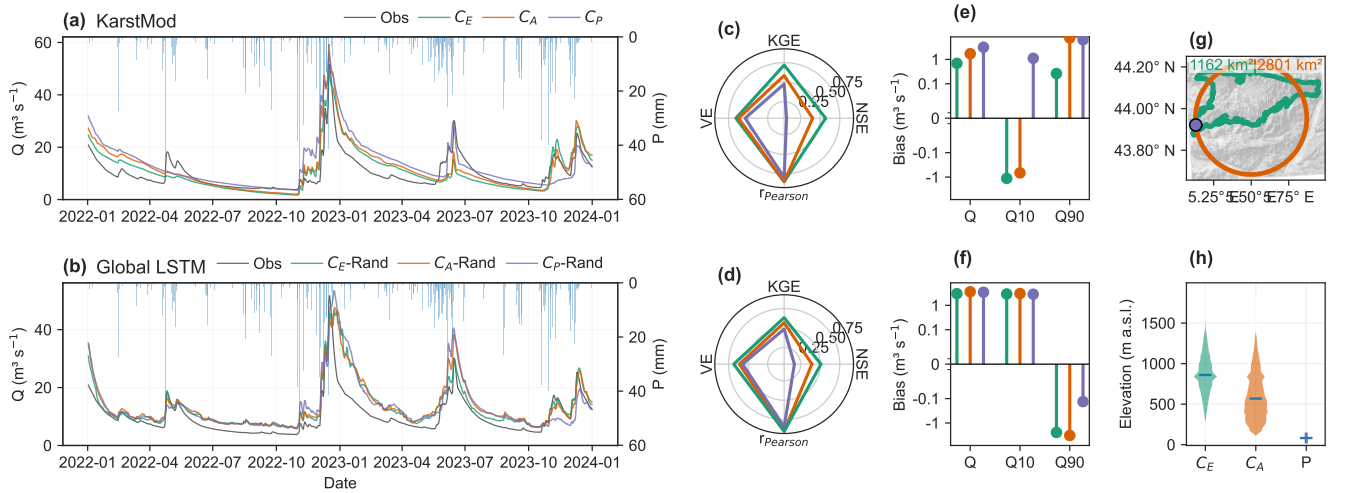


Figure S41. Detailed model performance for Source de la Sorgue (FR-0024).

Source du Grand Bief (FR-0034) - pluvial

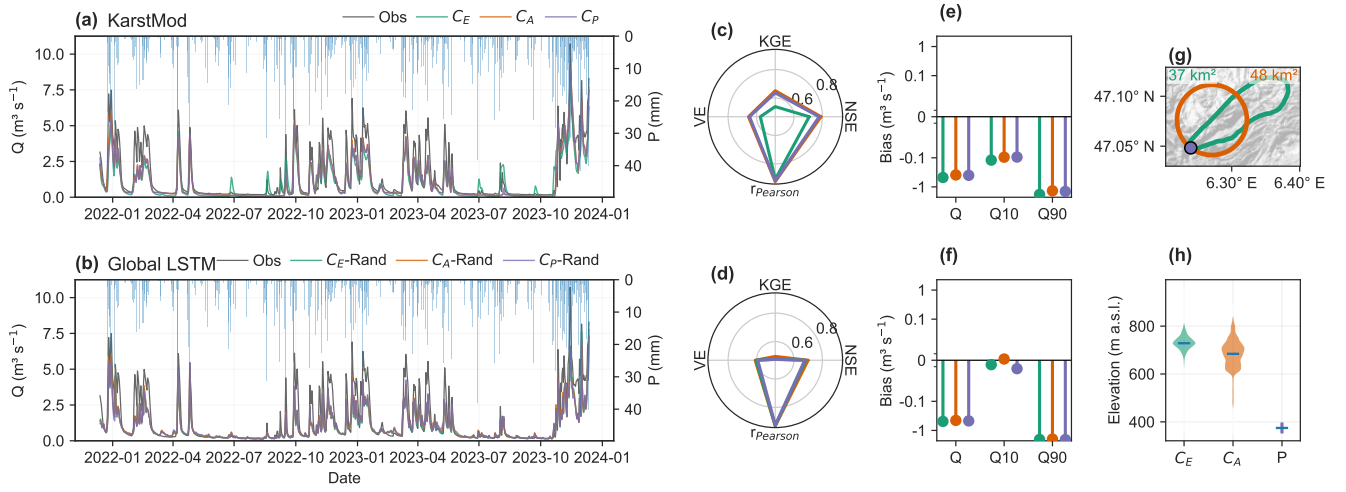


Figure S42. Detailed model performance for Source du Grand Bief (FR-0034).

Bilpa (SI-0012) - pluvial

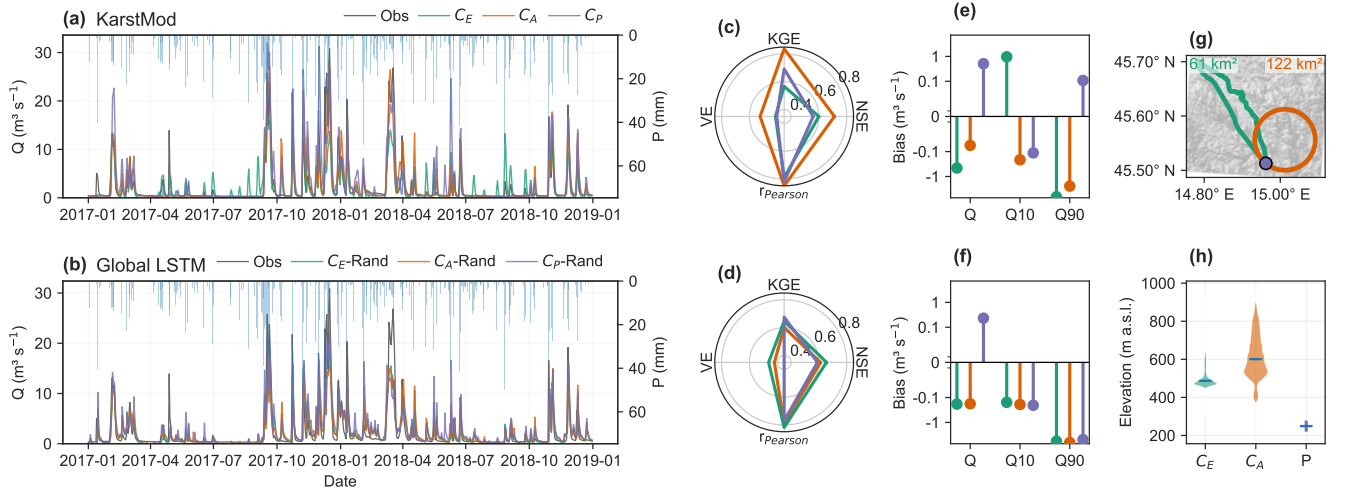


Figure S43. Detailed model performance for Bilpa (SI-0012). Expert-based catchment delineation (C_E): Petrič (2007); Petrič et al. (2021); Pavlič et al. (2008).

Ljubljana (SI-0016) - pluvial

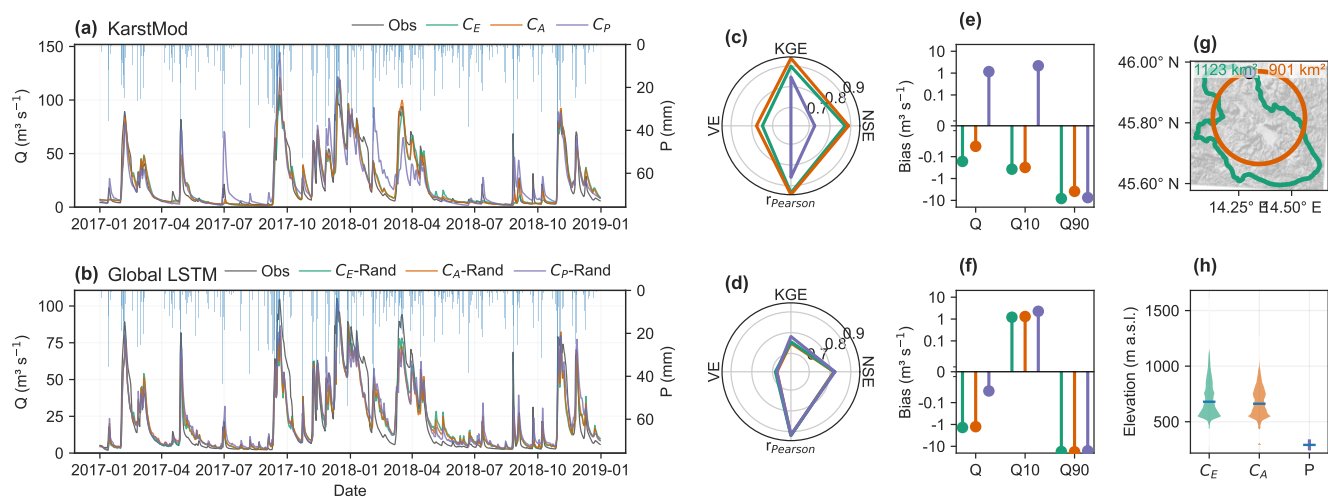


Figure S44. Detailed model performance for Ljubljana (SI-0016). Expert-based catchment delineation (C_E): Petrič (2007); Petrič et al. (2021); Pavlič et al. (2008).

Unica (SI-0035) - pluvial

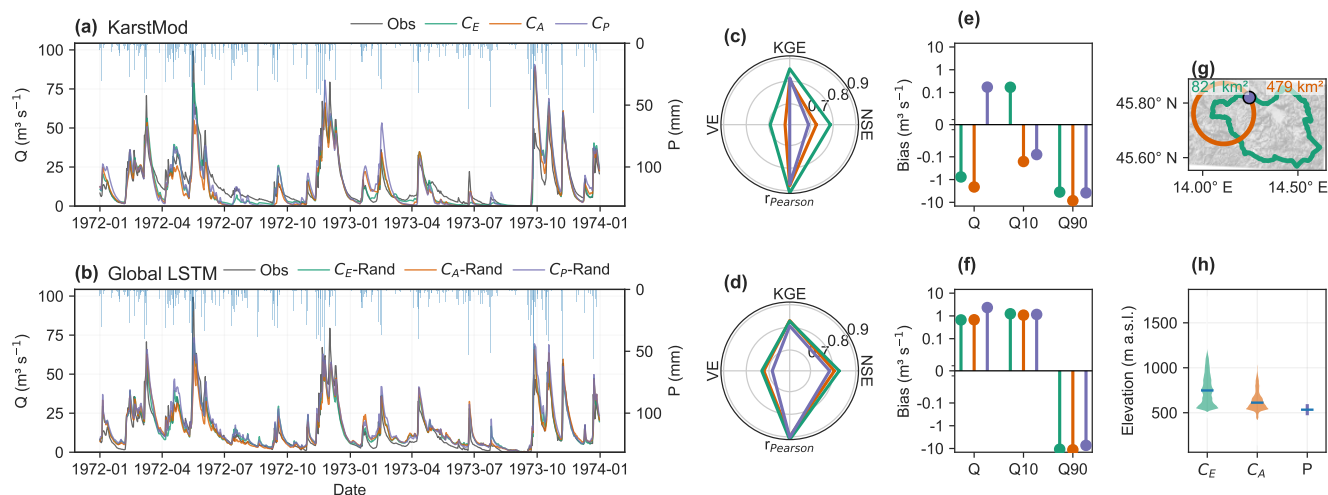


Figure S45. Detailed model performance for Unica (SI-0035). Expert-based catchment delineation (C_E): Petrič (2007); Petrič et al. (2021); Pavlič et al. (2008).

Poltarica (SI-0042) - pluvial

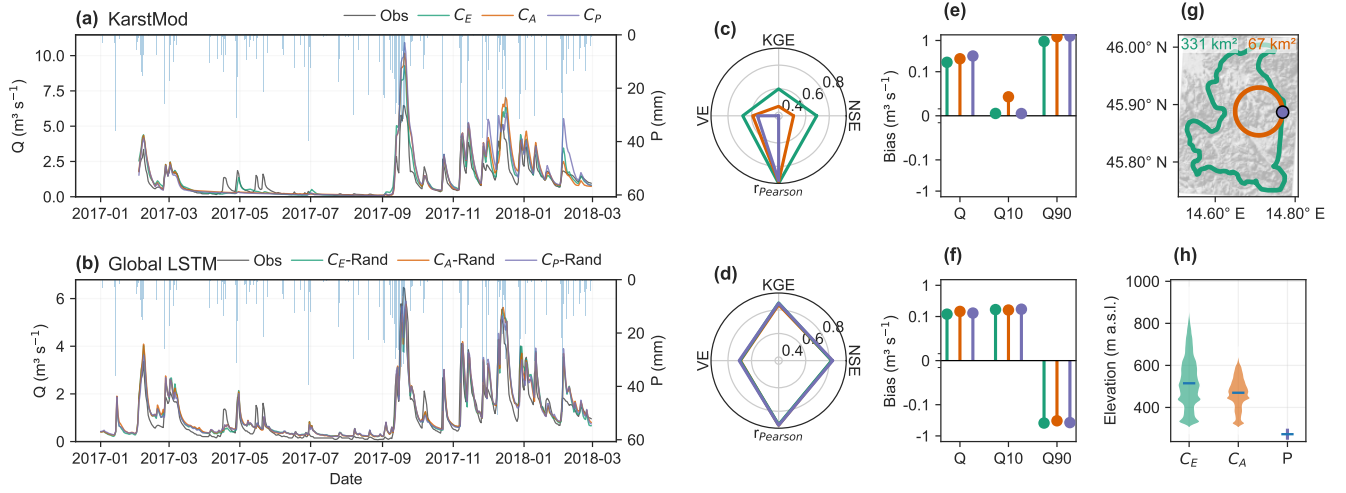


Figure S46. Detailed model performance for Poltarica (SI-0042). Expert-based catchment delineation (C_E): Petrič (2007); Petrič et al. (2021); Pavlič et al. (2008).

5 S1.4 Weak-seasonality cluster

Stubbachquelle (AT-0015) - weak seasonality

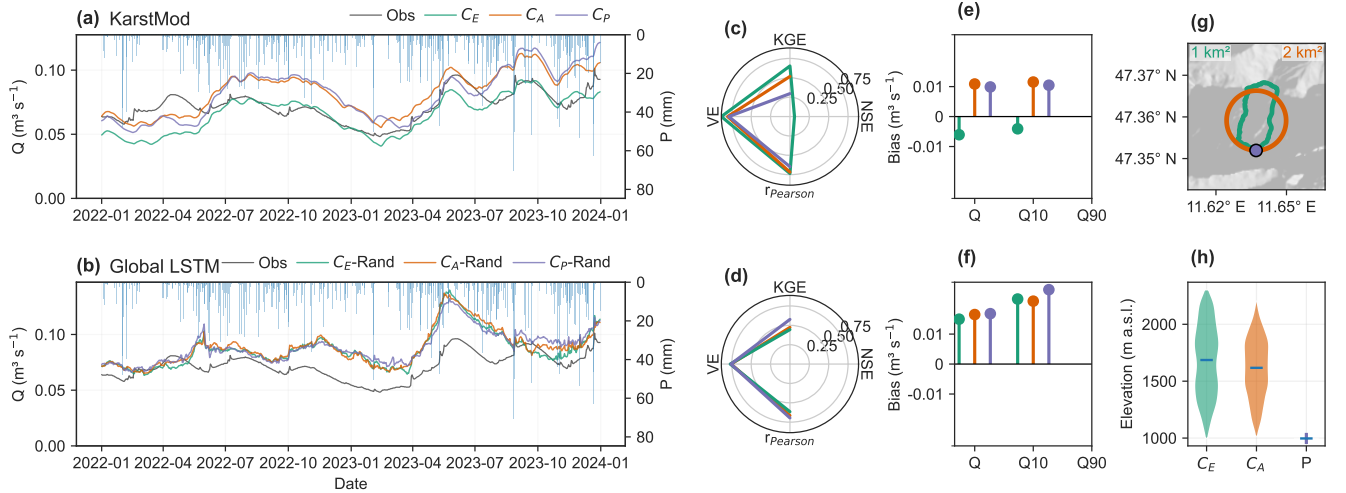


Figure S47. Detailed model performance for Stubbachquelle (AT-0015).

Lehnbachquellen (AT-0018) - weak seasonality

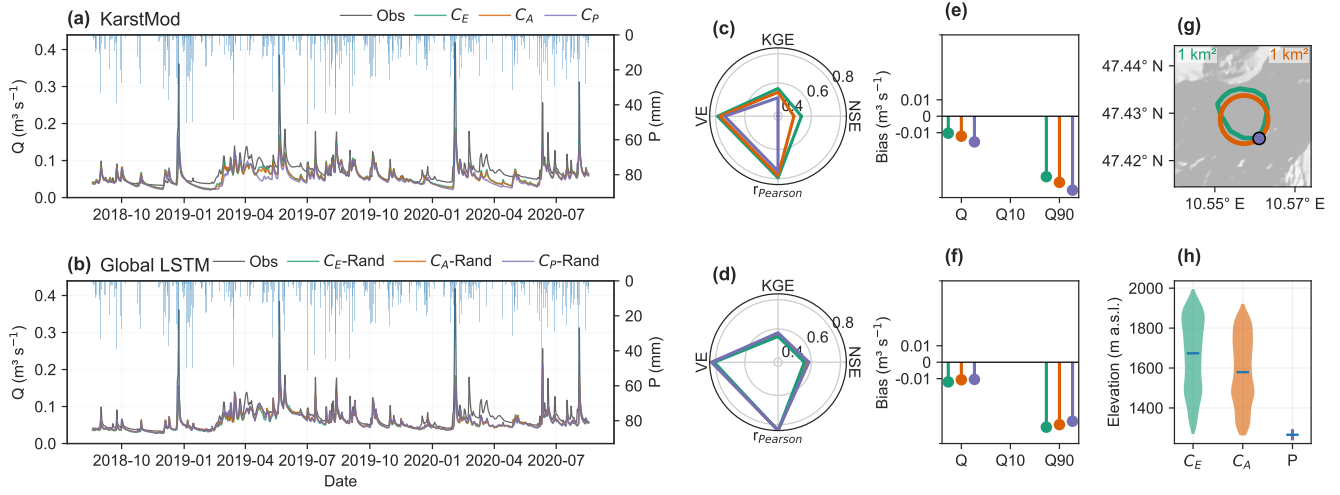


Figure S48. Detailed model performance for Lehnbachquellen (AT-0018).

Schwarzbodenquelle (AT-0019) - weak seasonality

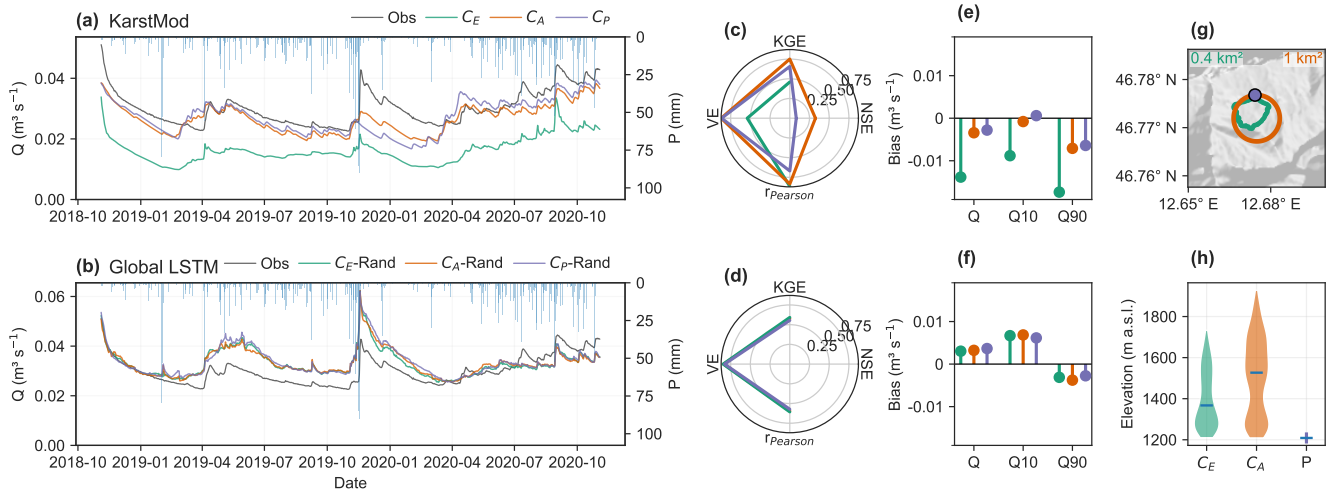


Figure S49. Detailed model performance for Schwarzbodenquelle (AT-0019).

Blaue Quelle (AT-0020) - weak seasonality

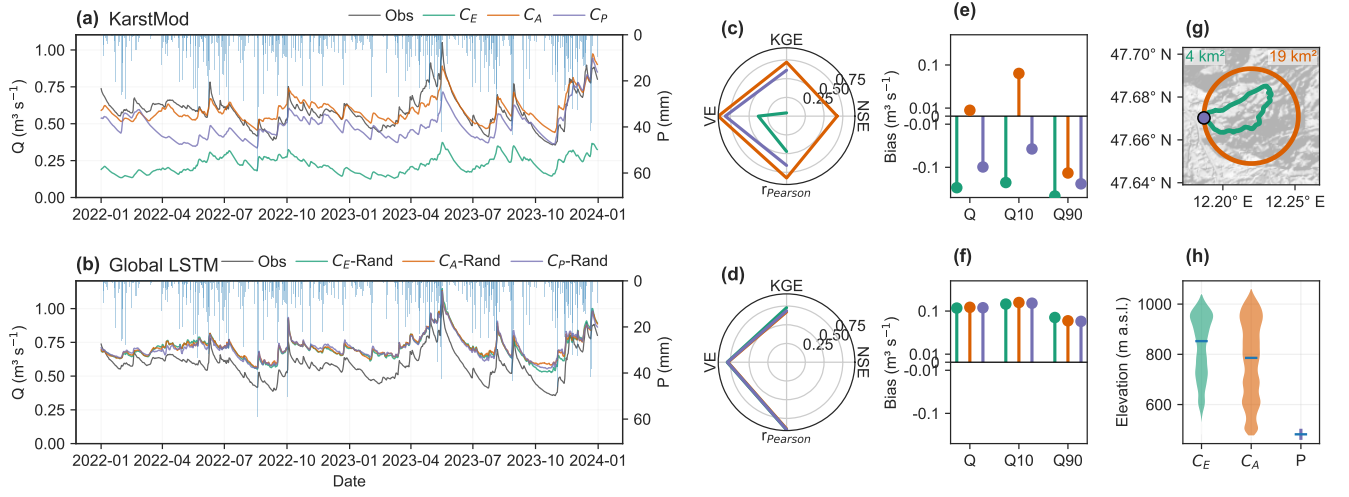


Figure S50. Detailed model performance for Blaue Quelle (AT-0020).

Moosbrunnquelle (AT-0023) - weak seasonality

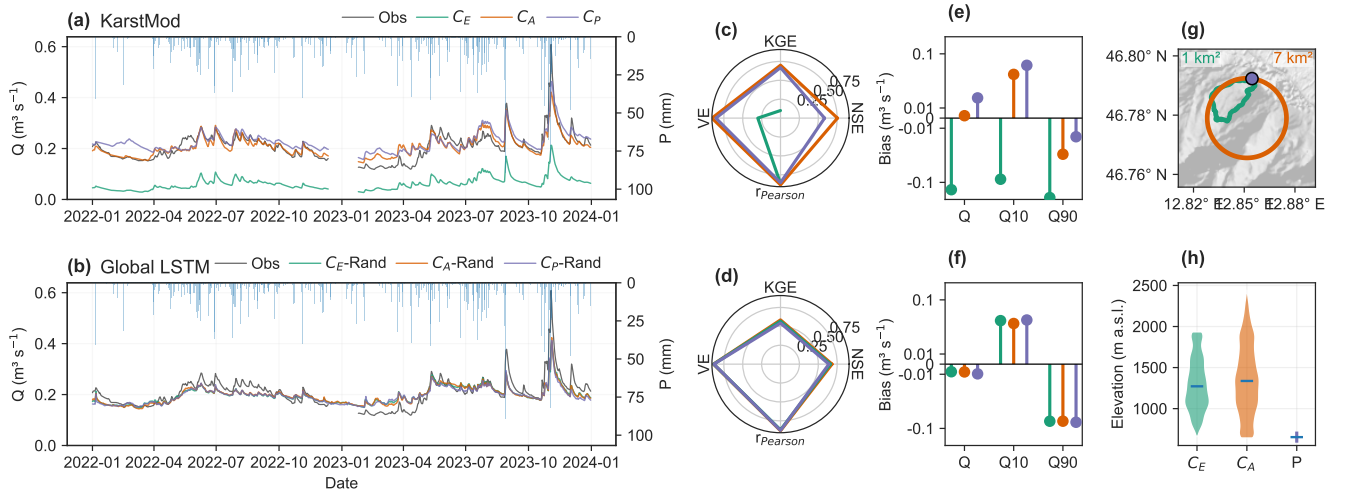


Figure S51. Detailed model performance for Moosbrunnquelle (AT-0023).

Fellbachquelle (AT-0033) - weak seasonality

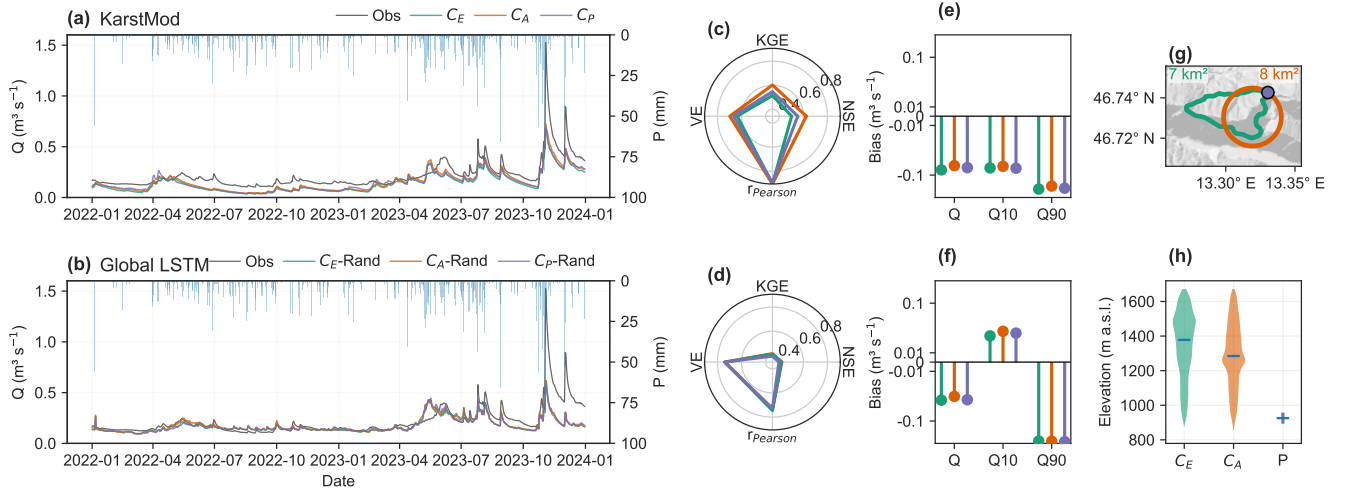


Figure S52. Detailed model performance for Fellbachquelle (AT-0033).

Hammerbachquelle (AT-0041) - weak seasonality

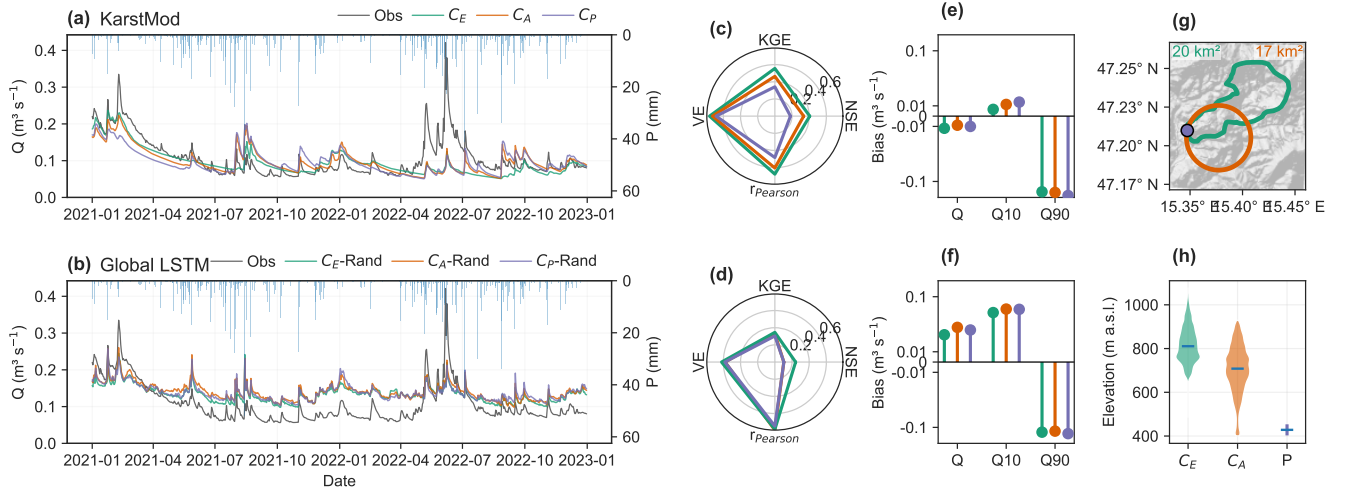


Figure S53. Detailed model performance for Hammerbachquelle (AT-0041).

Alfutzquelle (AT-0053) - weak seasonality

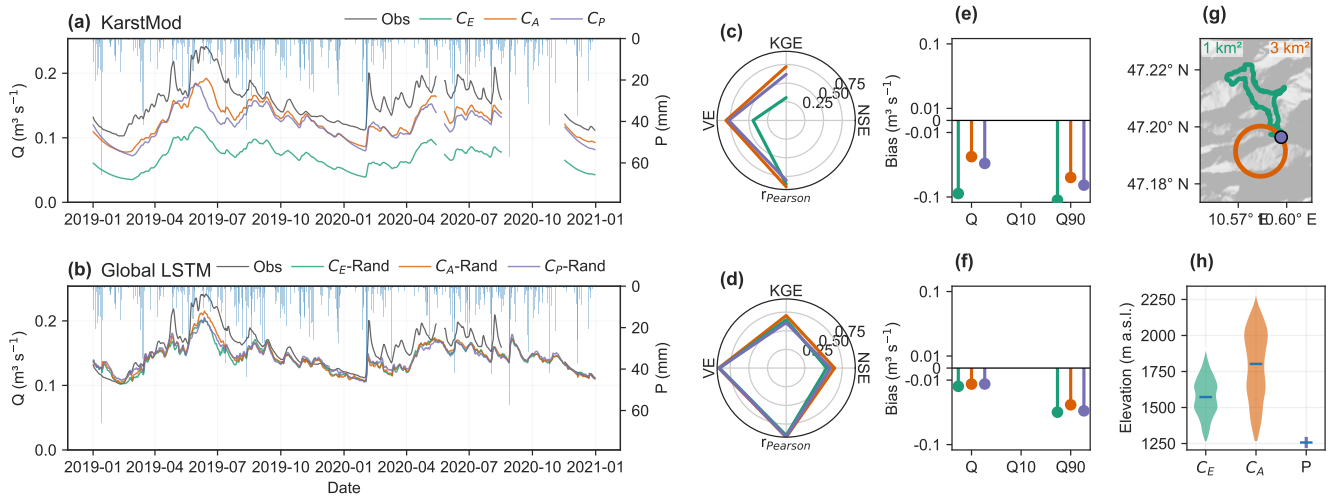


Figure S54. Detailed model performance for Alfutzquelle (AT-0053).

Heiterwandquelle (AT-0056) - weak seasonality

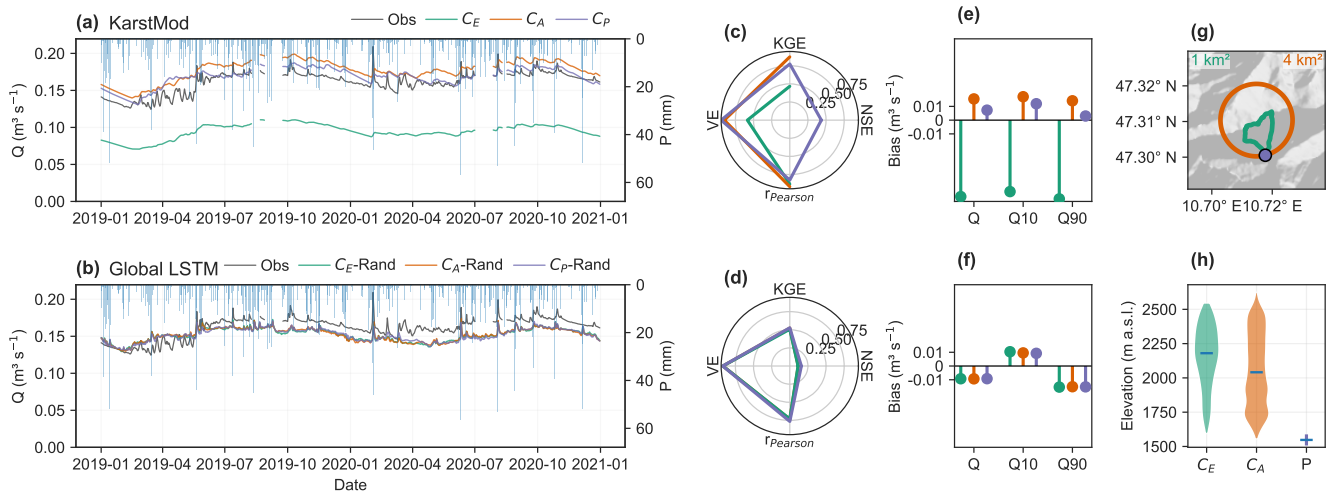


Figure S55. Detailed model performance for Heiterwandquelle (AT-0056).

Oswaldiquelle (AT-0058) - weak seasonality

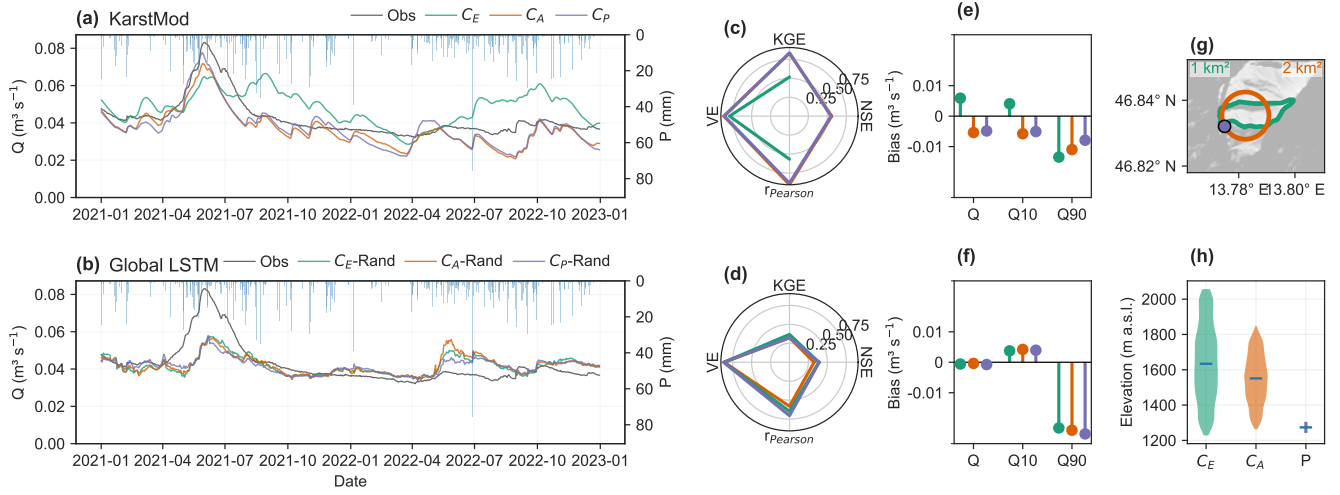


Figure S56. Detailed model performance for Oswaldiquelle (AT-0058).

Pöllauer Ursprung (AT-0062) - weak seasonality

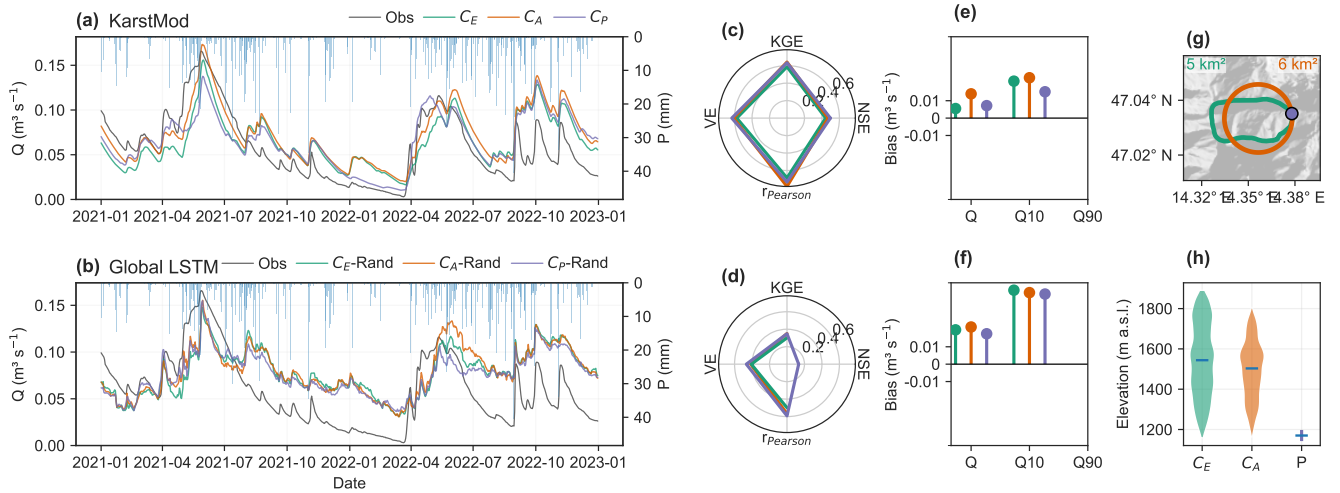


Figure S57. Detailed model performance for Pöllauer Ursprung (AT-0062).

Source Bossy (CH-0006) - weak seasonality

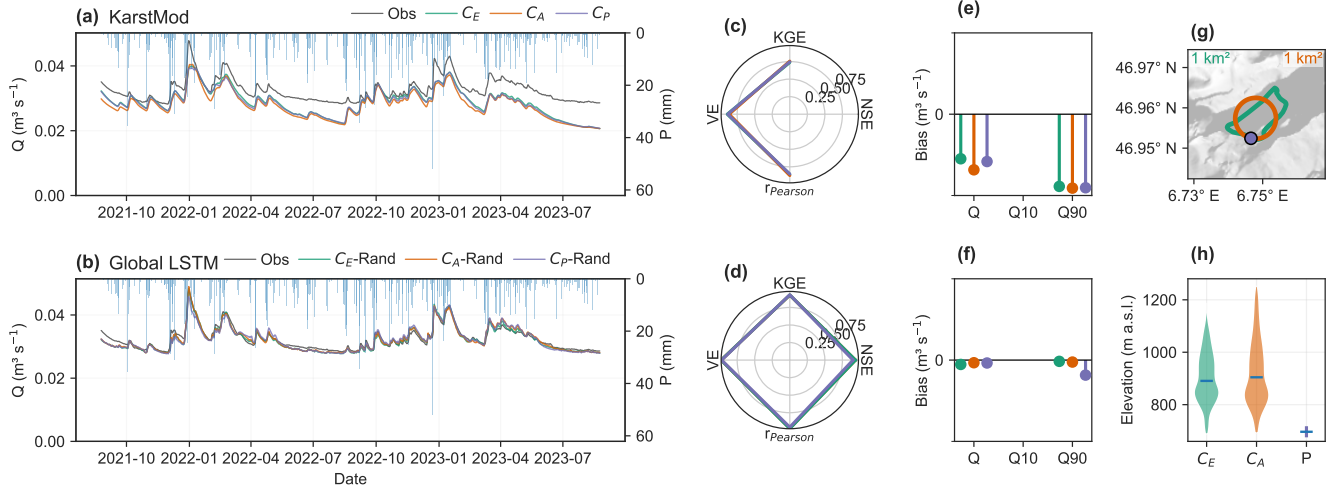


Figure S58. Detailed model performance for Source Bossy (CH-0006).

Source de la Doux (CH-0010) - weak seasonality

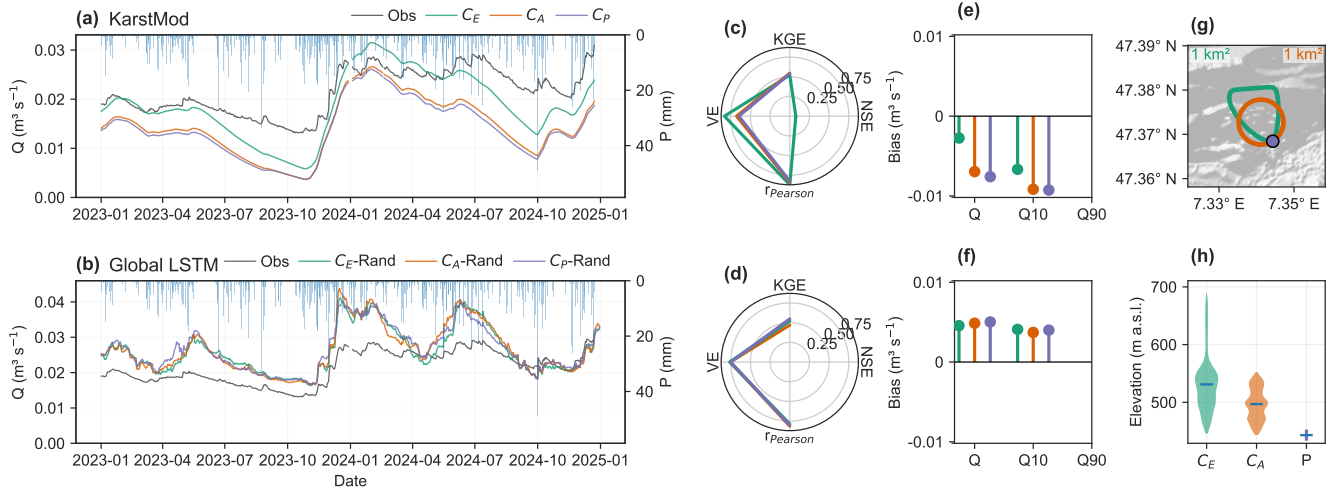


Figure S59. Detailed model performance for Source de la Doux (CH-0010).

Hammerrainquelle (CH-0016) - weak seasonality

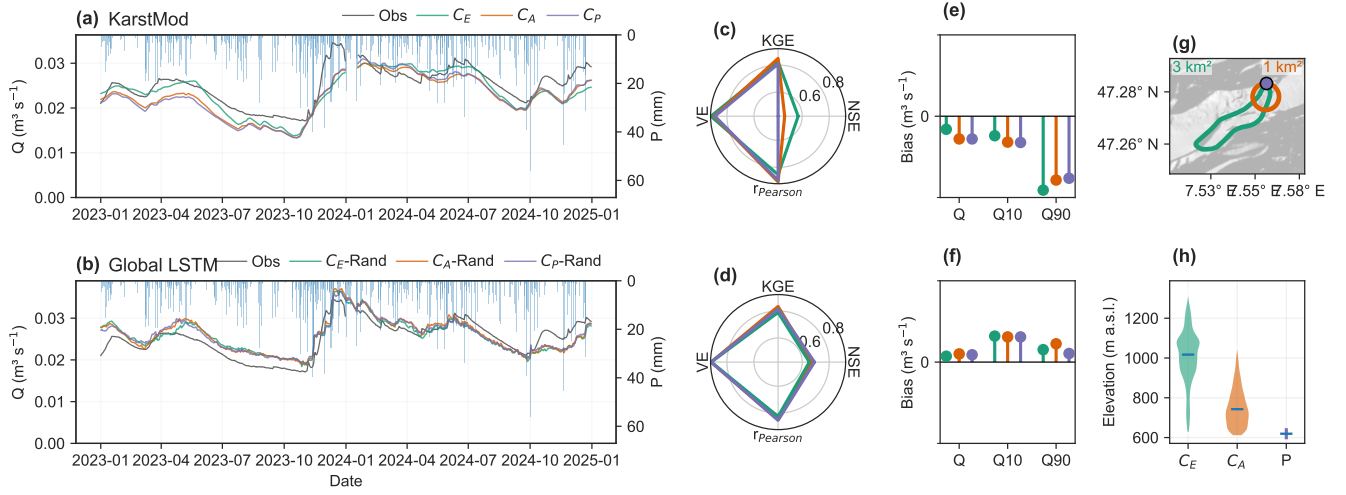


Figure S60. Detailed model performance for Hammerrainquelle (CH-0016).

Hüttenbachquelle (DE-0019) - weak seasonality

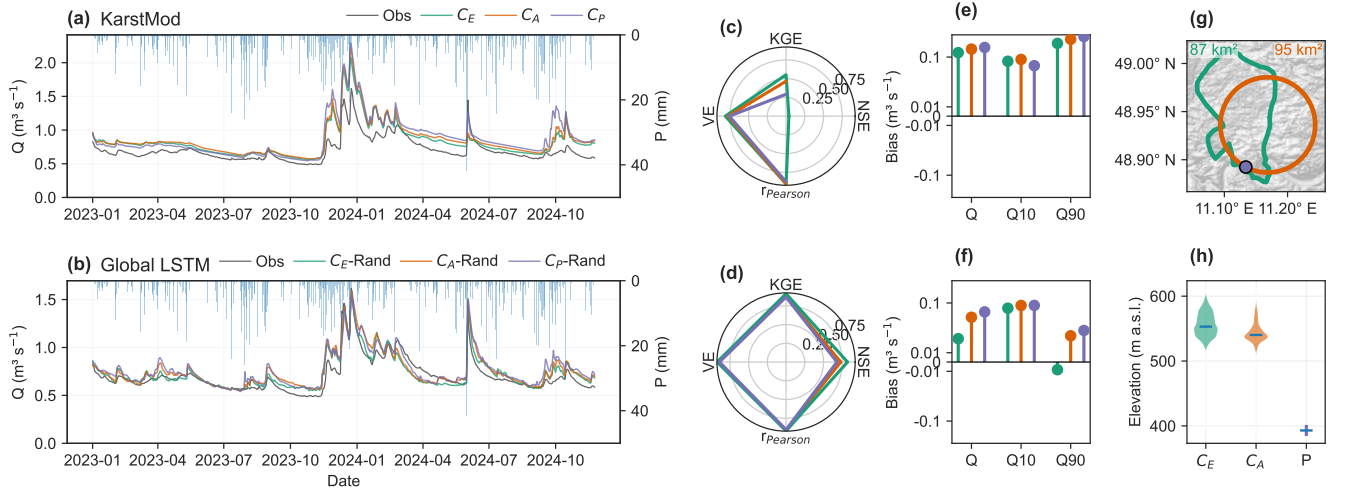


Figure S61. Detailed model performance for Hüttenbachquelle (DE-0019).

Malenščica (SI-0038) - weak seasonality

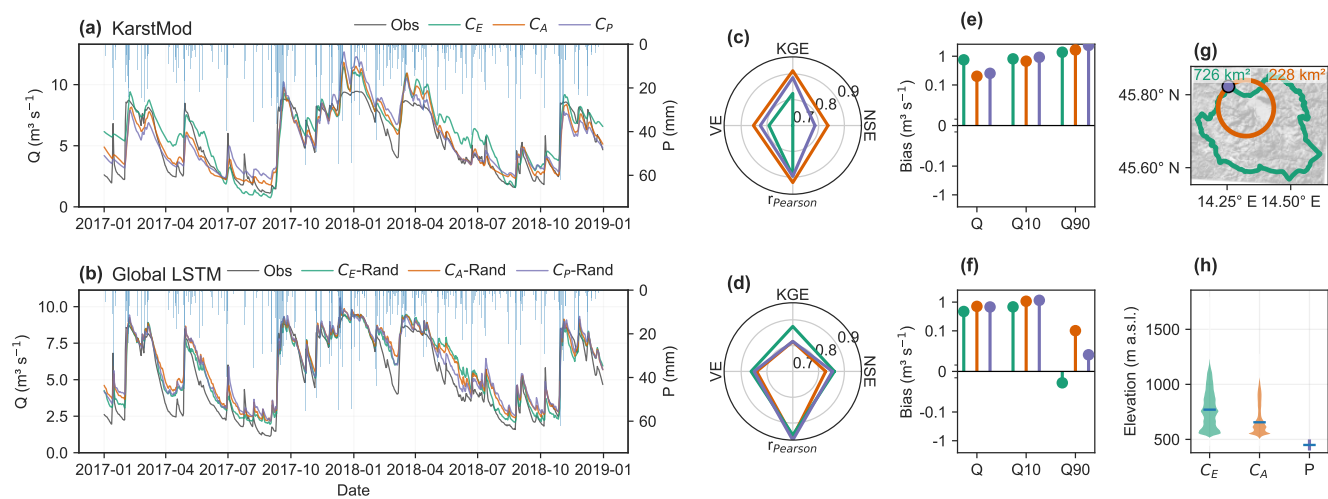


Figure S62. Detailed model performance for Malenščica (SI-0038). Expert-based catchment delineation (C_E): Petrič (2007); Petrič et al. (2021); Pavlič et al. (2008).

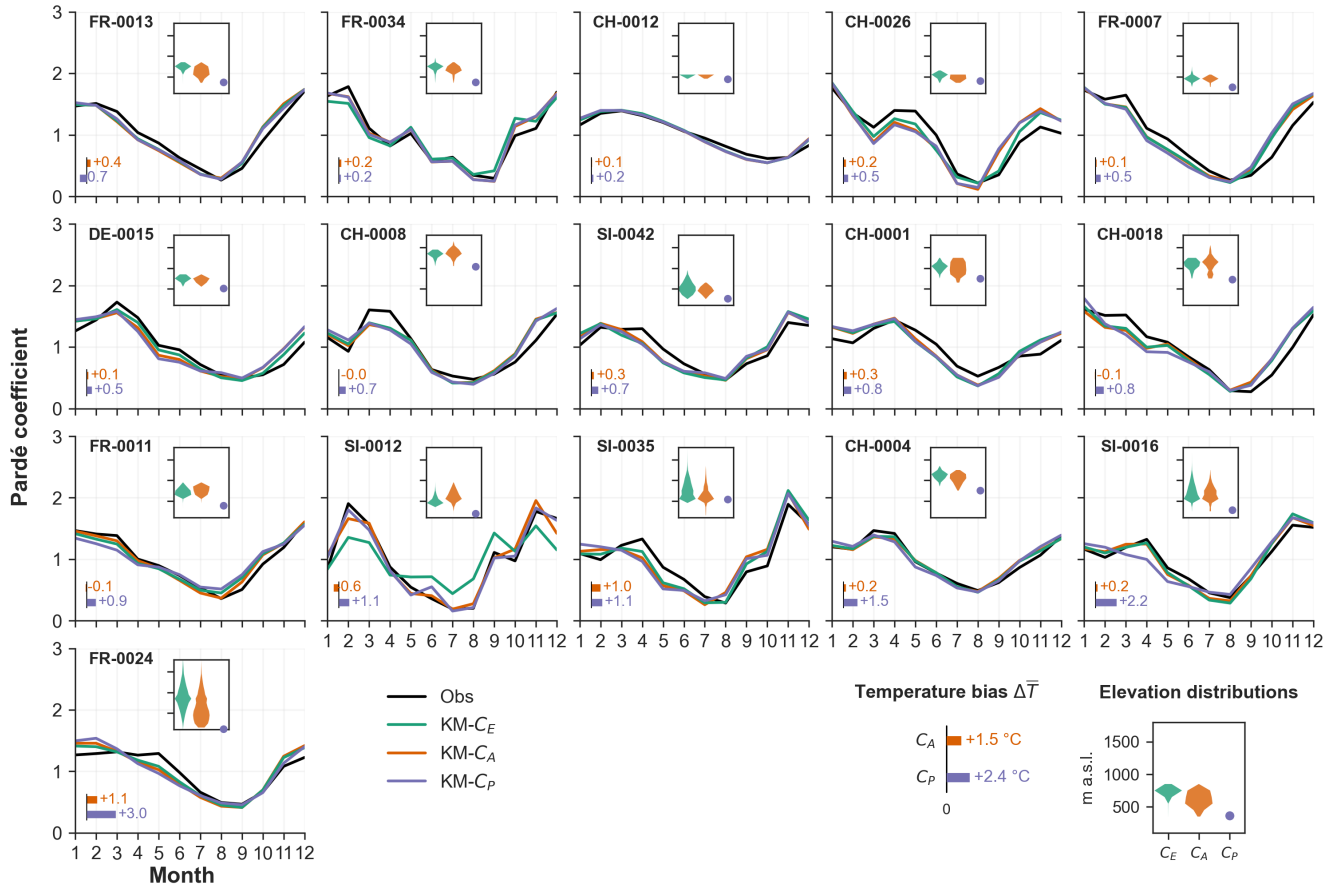


Figure S63. Observed and KarstMod-modelled spring discharge seasonality, shown as Pardé curves for each spring individually for the pluvial cluster. Each subplot shows four curves (observed, C_E , C_A , C_P), together with inset plots showing the elevation distributions of the three catchment representations and the mean temperature differences $\Delta\bar{T}$ for C_A and C_P relative to C_E . Curves are based on hydrological years with data availability > 80 %. Subplots are arranged in a grid, ordered left to right and top to bottom by increasing $\Delta\bar{T}(C_P - C_E)$. The two example insets in the lower-right corner illustrate the elevation distributions of the three catchment representations and the mean temperature differences $\Delta\bar{T}$ of C_A and C_P relative to C_E , as displayed for each spring. The example inset descriptions also apply to Figs. S64 and S65.

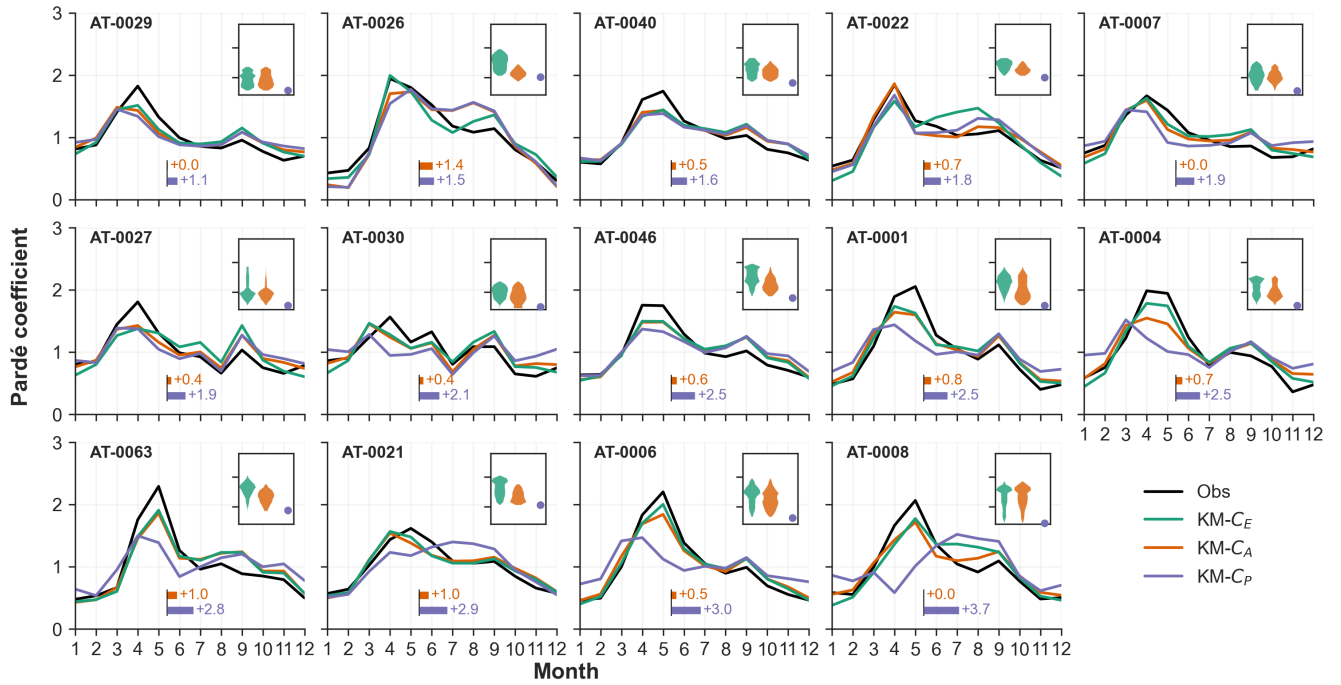


Figure S64. Observed and KarstMod-modelled spring discharge seasonality, shown as Pardé curves for each spring individually for the nivo-pluvial cluster.

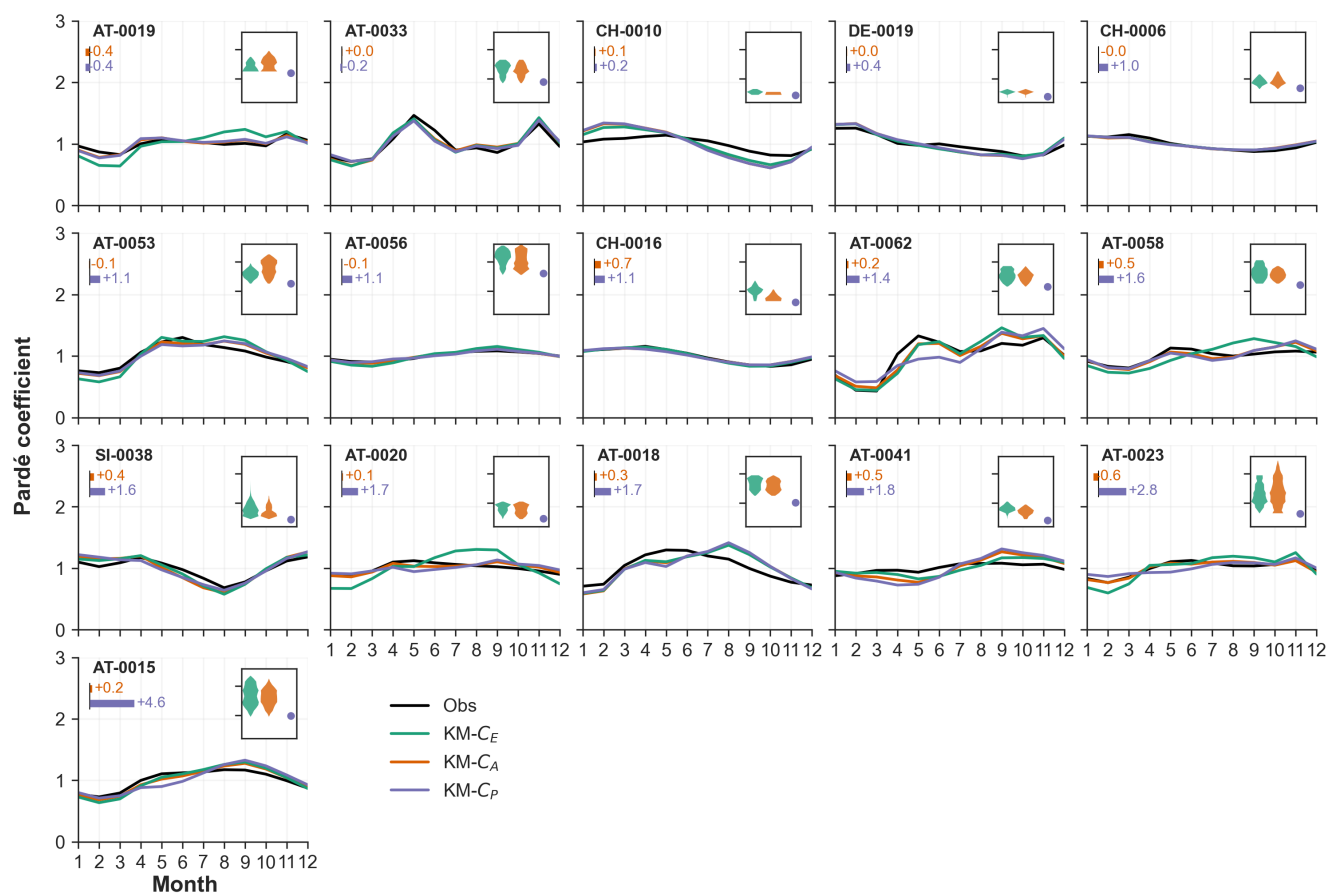


Figure S65. Observed and KarstMod-modelled spring discharge seasonality, shown as Pardé curves for each spring individually for the weak seasonality cluster.

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