The supplement provides details on the monthly correction factors applied to the observed historical E-OBS climate data (Sect. S1). An analysis of hydrological model results obtained when the model is forced with the simulated historical climate data and the root-zone storage capacity parameter derived from this data is provided in Sect. S2. The water balance equations, constitutive functions and model parameters are provided in Sects. S3 and S4.

S1 Monthly correction factors for E-OBS precipitation data **s2**

S2 Hydrological model results with the simulated historical climate data and root-zone storage capacity derived from this data **s3**

S3 Model equations **s7**

S4 Prior and posterior parameter distributions **s10**

S1 Monthly correction factors for E-OBS precipitation data

The precipitation of the observed historical E-OBS climate data is compared with the precipitation data derived from interpolated local station data for the period 2005 to 2017, as used in [**?**]. There is a good level of agreement between both datasets for most of the area of the Meuse basin. However, E-OBS precipitation data underestimate the interpolated station data at the center of the basin. Differences between both datasets are likely related to the lower amount of stations used in the development of the E-OBS dataset. Correction factors are derived and applied per month for the area where the underestimation of E-OBS precipitation exceeds 20 % (Fig. S1).

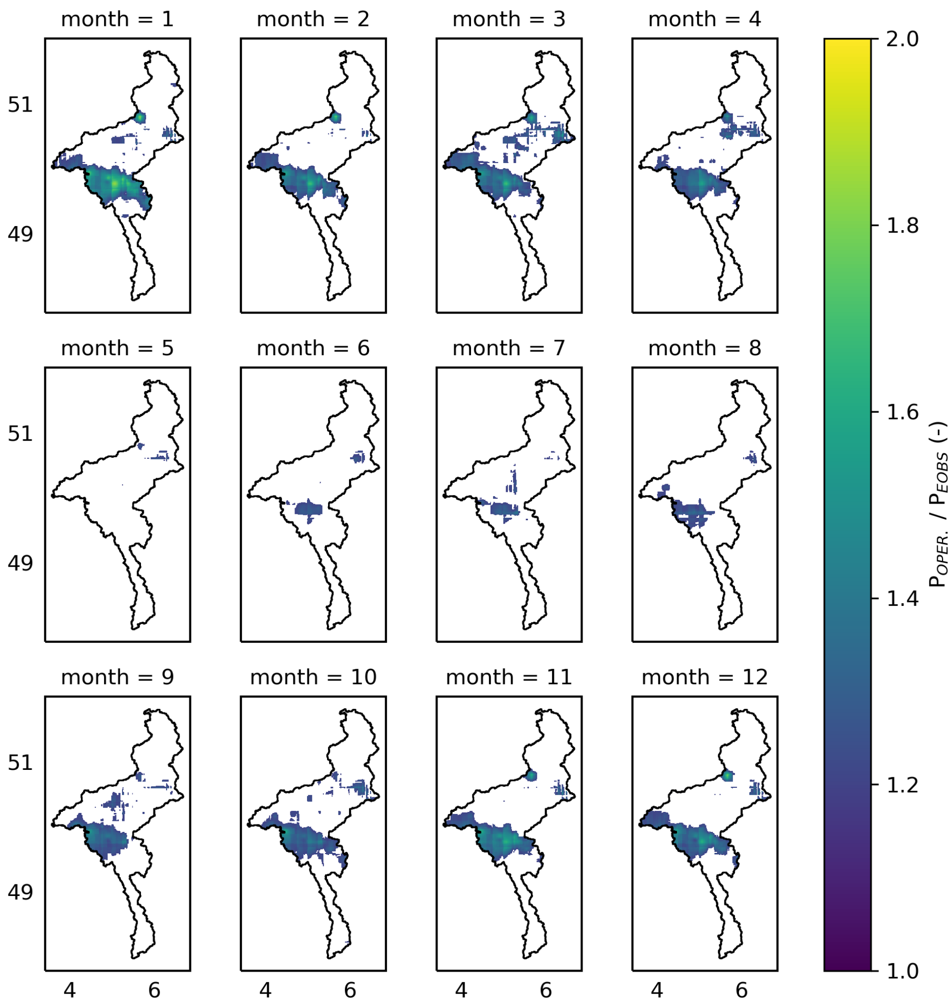

Figure S1: Monthly correction factors for the E-OBS precipitation data (P_{EOBS}) derived from the comparison with a precipitation dataset derived from interpolated local station data (denoted as $P_{\mathrm{OPER.}}$ in the legend).

S2 Hydrological model results with the simulated historical climate data and root-zone storage capacity derived from this data

In the manuscript, the observed historical E-OBS climate data is used to calibrate the model and to estimate the root-zone storage capacity parameter $S_{\mathrm{R,max,A}}$ for the historical climate and land-use conditions, as it is assumed to best represent current-day conditions. The parameter $S_{\mathrm{R,max,A}}$ is subsequently used for the model run forced with the simulated historical climate data. For the model runs with the simulated 2K climate data, we adapt the historical root-zone storage capacity $S_{\mathrm{R,max,A}}$ by adding the increase in storage deficit between the simulated historical and 2K climate data to the observed historical storage deficit to obtain $S_{\mathrm{R,max,B}}$.

Another approach would have been to estimate an alternative root-zone storage capacity parameter $S_{\mathrm{R,max,A1}}$ for the historical period, using the simulated historical climate data instead of the observed historical E-OBS climate data. This has the advantage that potential biases in the simulated historical climate data are directly corrected for in the estimation of the root-zone storage capacity parameter. However, these biases may also result in a less plausible spatial representation of the root-zone storage capacity across catchments of the Meuse basin.

In the estimation of the root-zone storage capacity $S_{\mathrm{R,max,A1}}$ using the simulated historical climate data, the long term transpiration is calculated according to $E_{\mathrm{R}} = P_{\mathrm{E,hist}} - Q_{\mathrm{obs}}/P_{\mathrm{hist}} \cdot P_{\mathrm{hist}}$, with the subscript $_{\mathrm{hist}}$ to denote the simulated historical climate data.

The simulated historical precipitation overestimates the observed historical precipitation with approximately $+9\,\%$ (Fig. S2). This implies a lower runoff coefficient and a larger evaporative index in comparison to using the observed historical climate data with the observed streamflow. The higher evaporative index, in turn, results in approaximately $+7\,\%$ larger root-zone storage capacity $S_{\mathrm{R,max,A1}}$ in comparison to $S_{\mathrm{R,max,A}}$.

The model run forced with the simulated historical climate data and the larger root-zone storage capacity $S_{\mathrm{R,max,A1}}$ results in slightly lower peak flows and mean monthly winter streamflow in comparison to the model run with the simulated historical climate data and the $S_{\mathrm{R,max,A}}$ parameter (Fig. S3). However, differences are relatively small and the hydrological behavior of the three historical runs (E-OBS with $S_{\mathrm{R,max,A}}$, simulated historical with $S_{\mathrm{R,max,A}}$ and simulated historical with $S_{\mathrm{R,max,A1}}$) is relatively similar (Fig. S3). The model runs forced with the simulated historical climate data and with both $S_{\mathrm{R,max,A}}$ and $S_{\mathrm{R,max,A1}}$ as model parameter also show similar performance metrics (Fig. S4).

These analyses suggest that hydrological model performance for the historical period is slightly improved if the root-zone storage capacity parameter is adapted to the used forcing data. However, these improvements between using $S_{\mathrm{R,max,A}}$ and $S_{\mathrm{R,max,A1}}$ in model runs forced with the simulated historical climate data are relatively small.

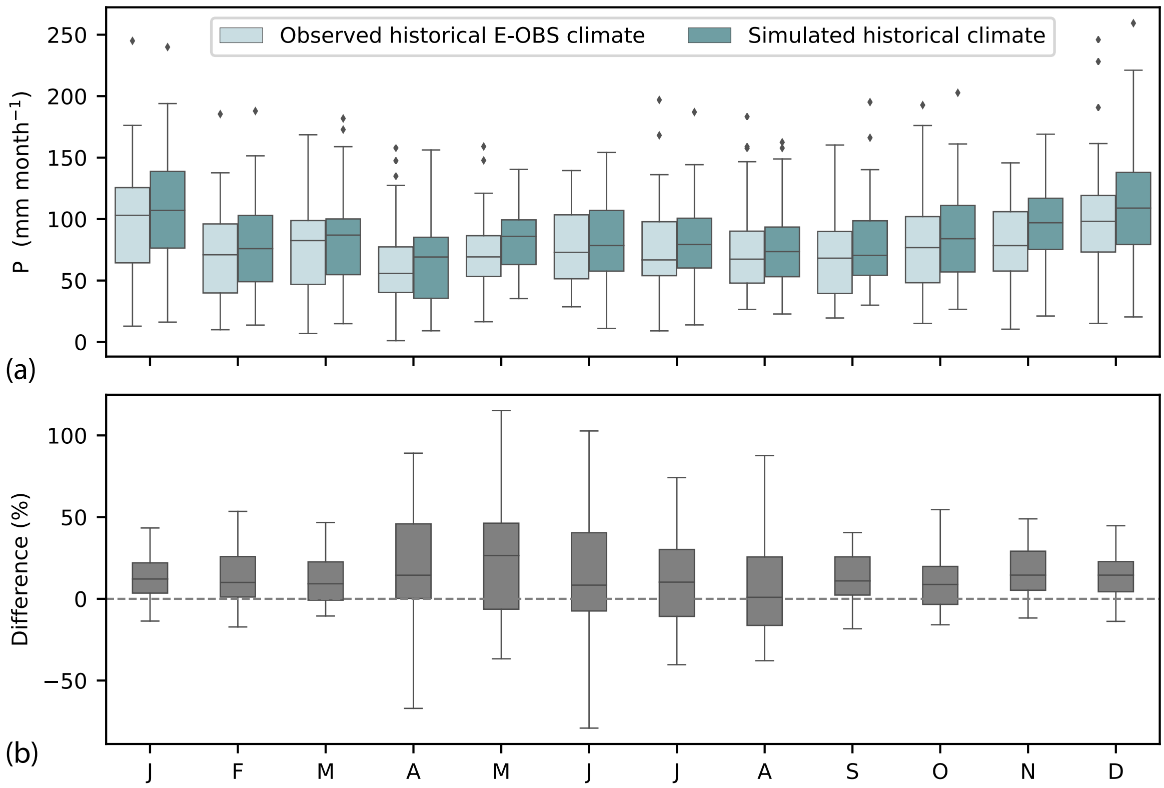

Figure S2: **(a)** Mean monthly precipitation of the observed E-OBS and simulated historical climate data for the period 1980-2018 and **(b)** difference between the simulated and observed monthly precipitation (%).

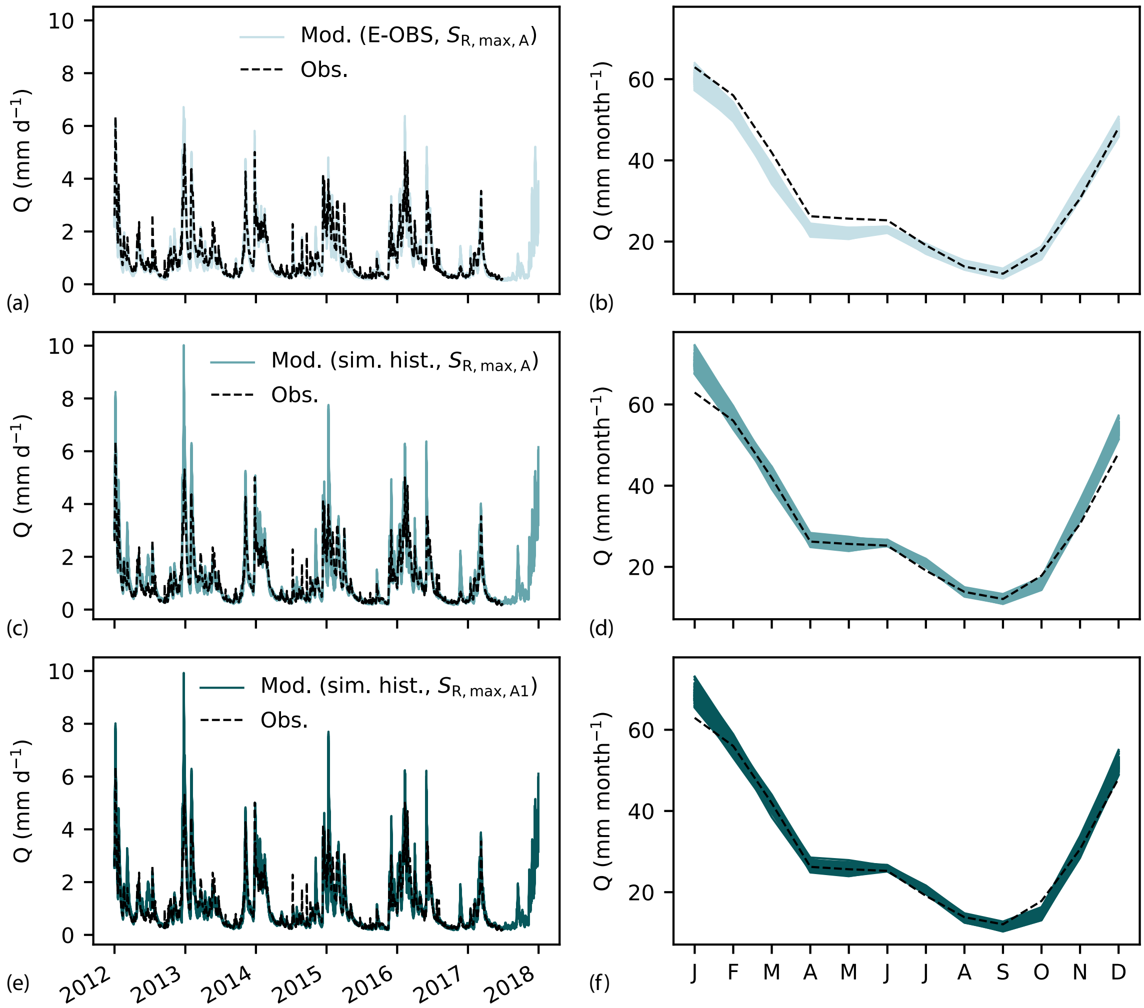

Figure S3: Observed and modeled hydrographs and mean monthly streamflow at Borgharen for the ensemble of parameter sets retained as feasible after calibration when the model is: **(a,b)** forced with E-OBS historical data and using $S_{\mathrm{R,max,A}}$ as model parameter, **(c,d)** forced with the simulated historical climate data using $S_{\mathrm{R,max,A}}$ as model parameter, and **(e,f)** forced with the simulated historical climate data using $S_{\mathrm{R,max,A1}}$ as model parameter. The panels **(a,b,c,d)** are repeated from the manuscript to allow for a better comparison with the added panels **(e,f)**.

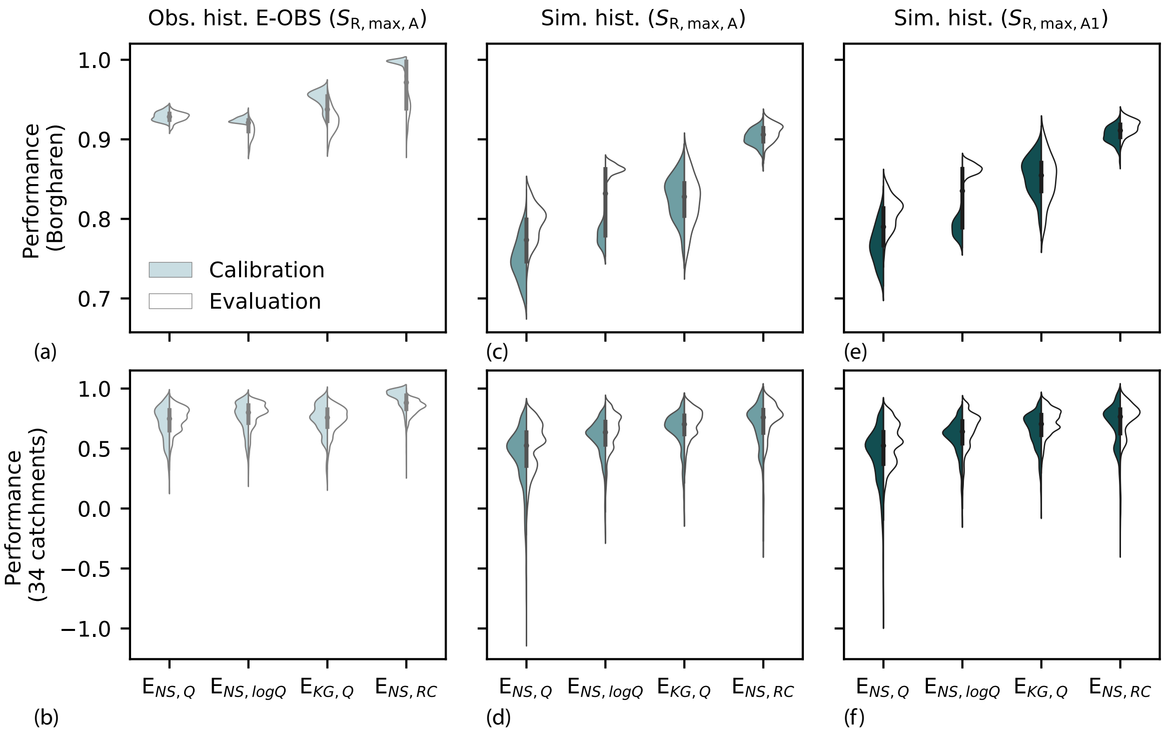

Figure S4: Streamflow model performance during calibration and evaluation for the four objective functions when the model is forced with (**a**,**b**) observed historical E-OBS data and $S_{\mathrm{R,max,A}}$ as model parameter, (**c**,**d**) simulated historical climate data and $S_{\mathrm{R,max,A}}$ as model parameter, and (**e**,**f**) simulated historical climate data and $S_{\mathrm{R,max,A1}}$ as model parameter at (**a**,**c**,**e**) Borgharen and (**b**,**d**,**f**) for the ensemble of nested catchments in the Meuse basin. The four objective functions are the Nash-Sutcliffe efficiencies of streamflow, logarithm of streamflow and monthly runoff coefficient ($E_{\mathrm{NS,Q}}$, $E_{\mathrm{NS,logQ}}$, $E_{\mathrm{NS,RC}}$) as well as the Kling-Gupta efficiency of streamflow ($E_{\mathrm{KG,Q}}$). Note the different y-axis between rows. The panels **(a,b,c,d)** are repeated from the manuscript to allow for a better comparison with the added panels **(e,f)**.

S3 Model equations

Symbols used to define the different fluxes and storages in the model schematization (see Figure 3 of the manuscript) are detailed in Table S1 and Table S2. Definitions of the symbols used for the parameters are provided in Sect. S4. Water balance and constitutive equations are provided in Table S3 and in Table S4.

Table S1: Definitions of the symbols used to denote the different model fluxes. For each class, the subscripts P, H and W are added in Figure 3 of the manuscript to denote plateau, hillslope and wetland, e.g. $E_{\mathrm{I,W}}$ indicates interception evaporation from the wetland class.

Fluxes (mm d^{-1})	Definition
P	Precipitation
P_{R}	Rainfall
P_{S}	Snowfall
P_{M}	Snow melt
E_{P}	Potential evaporation
E_{W}	Evaporation from snow storage
E_{I}	Evaporation from interception
E_{R}	Evaporation from the root-zone storage
P_{E}	Effective precipitation
R_{R}	Outflow from the root-zone storage
R_{RS}	Recharge to the slow storage
R_{RF}	Recharge to the fast storage
R_{P}	Percolation
R_{C}	Capillary rise
Q_{F}	Fast runoff
Q_{S}	Slow runoff
Q	Streamflow

Table S2: Definitions of the symbols used to denote the different storages.

Storage (mm)	Definition
S_{W}	Snow storage
S_{I}	Interception storage
S_{R}	Root-zone storage
S_{F}	Fast runoff storage
S_{S}	Slow runoff storage

Table S3: Water balance equations for each class of the wflow_FLEX-Topo model. The three classes share a common groundwater storage S_{S}.

Water balance equation	Plateau	Hillslope	Wetland
$\mathrm{d}S_{\mathrm{W}}/\mathrm{d}t = P_{\mathrm{S}} - E_{\mathrm{W}} - P_{\mathrm{M}}$	✓	✓	✓
$\mathrm{d}S_{\mathrm{I}}/\mathrm{d}t = P_{\mathrm{R}} - E_{\mathrm{I}} - P_{\mathrm{E}}$	✓	✓	✓
$\mathrm{d}S_{\mathrm{R}}/\mathrm{d}t = P_{\mathrm{E}} + P_{\mathrm{M}} - E_{\mathrm{R}} - R_{\mathrm{RS}} - R_{\mathrm{RF}} - R_{\mathrm{P}}$	✓		
$\mathrm{d}S_{\mathrm{R}}/\mathrm{d}t = P_{\mathrm{E}} + P_{\mathrm{M}} - E_{\mathrm{R}} - R_{\mathrm{RS}} - R_{\mathrm{RF}}$		✓	
$\mathrm{d}S_{\mathrm{R}}/\mathrm{d}t = P_{\mathrm{E}} + P_{\mathrm{M}} - E_{\mathrm{R}} - R_{\mathrm{RS}} - R_{\mathrm{RF}} + R_{\mathrm{C}}$			✓
$\mathrm{d}S_{\mathrm{F}}/\mathrm{d}t = R_{\mathrm{RF}} - Q_{\mathrm{F}}$	✓	✓	✓
$\mathrm{d}S_{\mathrm{S}}/\mathrm{d}t = R_{\mathrm{RS}} + R_{\mathrm{P}} - Q_{\mathrm{S}}$	✓		
$\mathrm{d}S_{\mathrm{S}}/\mathrm{d}t = R_{\mathrm{RS}} - Q_{\mathrm{S}}$		✓	
$\mathrm{d}S_{\mathrm{S}}/\mathrm{d}t = -R_{\mathrm{C}} - Q_{\mathrm{S}}$			✓
$Q = Q_{\mathrm{S}} + Q_{\mathrm{F,P}} + Q_{\mathrm{F,H}} + Q_{\mathrm{F,W}}$			

Table S4: Constitutive functions. T denotes temperature. The groundwater storage is shared between all classes. Symbols for the parameters are detailed in Table S5.

Constitutive functions	Plateau	Hillslope	Wetland
Snow			
$P_{\mathrm{S}} = \begin{cases} \mathsf{P}, & \text{if } T < T_{\mathrm{T}} \\ 0, & \text{if } T \geq T_{\mathrm{T}} \end{cases}$	✓	✓	✓
$E_{\mathrm{W}} = \min(E_{\mathrm{P}}, S_{\mathrm{W}}/\mathsf{dt})$	✓	✓	✓
$P_{\mathrm{M}} = \begin{cases} 0, & \text{if } T < T_{\mathrm{T}} \\ \min(\mathsf{F}_{\mathrm{M}} \cdot (T - T_{\mathrm{M}}), S_{\mathrm{W}}/\mathrm{d}t), & \text{if } T \geq T_{\mathrm{T}} \end{cases}$	✓	✓	✓
Interception			
$\overline{S_{\mathrm{I}}} = S_{\mathrm{I}}/I_{\max}$	✓	✓	✓
$P_{\mathrm{R}} = \begin{cases} 0, & \text{if } T < T_{\mathrm{T}} \\ \mathsf{P}, & \text{if } T \geq T_{\mathrm{T}} \end{cases}$	✓	✓	✓
$P_{\mathrm{E}} = \max(0, (S_{\mathrm{I}} - I_{\max})/\mathrm{d}t)$	✓	✓	✓
$E_{\mathrm{I}} = \min(E_{\mathrm{P}} - E_{\mathrm{W}}, (S_{\mathrm{I}} - I_{\max})/\mathrm{d}t)$	✓	✓	✓
Root-zone			
$\overline{S_{\mathrm{R}}} = S_{\mathrm{R}}/S_{\mathrm{R,max}}$	✓	✓	✓
$R_{\mathrm{R}} = R_{\mathrm{RS}} + R_{\mathrm{RF}}$	✓	✓	
$E_{\mathrm{R}} = \min((E_{\mathrm{P}} - E_{\mathrm{I}}) \cdot \min(\overline{S_{\mathrm{R}}}/L_{\mathrm{P}}, 1), S_{\mathrm{U}}/\mathrm{d}t)$	✓	✓	✓
$R_{\mathrm{R}} = (P_{\mathrm{E}} + P_{\mathrm{M}}) \cdot (1 - (1 - \overline{S_{\mathrm{R}}})^{\beta})$	✓	✓	✓
$R_{\mathrm{P}} = R_{\mathrm{P,max}} \cdot \overline{S_{\mathrm{R}}}$	✓		
$R_{\mathrm{C}} = R_{\mathrm{C,max}} \cdot (1 - \overline{S_{\mathrm{R}}})$			✓
Fast storage			
$R_{\mathrm{RF}} = R_{\mathrm{R}} \cdot (1 - D)$	✓	✓	
$R_{\mathrm{RF}} = R_{\mathrm{R}}$			✓
$Q_{\mathrm{F}} = K_{\mathrm{F}}^{-1} \cdot S_{\mathrm{F}}^{\alpha}$	✓	✓	
$Q_{\mathrm{F}} = K_{\mathrm{F}}^{-1} \cdot S_{\mathrm{F}}$			✓
Slow storage			
$R_{\mathrm{RS}} = R_{\mathrm{R}} \cdot D$	✓	✓	
$Q_{\mathrm{S}} = K_{\mathrm{S}}^{-1} \cdot S_{\mathrm{S}}$	✓	✓	✓

S4 Prior and posterior parameter distributions

A description of model parameters, units, prior and posterior ranges is provided in Table S5.

Table S5: Calibrated model parameters, units and prior range (*MRC denotes the value determined with a master recession curve ± 30 %).

Parameter	unit	Description	Prior range	Plateau	Hillslope	Wetland
T_{T}	°C	Threshold temp. snow and rain	0.7 - 1.9	0.7 - 1.7	0.7 - 1.7	0.7 - 1.7
T_{M}	°C	Threshold temp. snow melt	0.7 - 2.3	0.8 - 2.2	0.8 - 2.2	0.8 - 2.2
F_{M}	mm d^{-1} °C^{-1}	Degree day factor	2.0 - 5.0	2.3 - 5.0	2.3 - 5.0	2.3 - 5.0
I_{max}	mm	Max. interception capacity	0.5 - 4.0	0.5 - 3.0	0.9 - 4.0	0.5 - 3.0
β	-	Shape parameter	0.2 - 0.4	0.2 - 0.4	0.2 - 0.4	0.2 - 0.4
L_{P}	-	Evap. reduction coefficient	0.1 - 0.6	0.1 - 0.6	0.1 - 0.4	0.1 - 0.6
$R_{\mathrm{C,max,W}}$	mm d^{-1}	Max. capillary rise	0.1 - 0.5			0.1 - 0.5
$R_{\mathrm{P,max,P}}$	mm d^{-1}	Max. percolation	0.05 - 0.72	0.05 - 0.72		
α	-	Non-linear coefficient	1 - 1.8	1.0 - 1.8	1.0 - 1.4	
K_{F}	d	Fast recession time scale	10 - 100	10 - 100	10 - 100	10 - 100
D	-	Fraction to slow storage	0.04 - 1	0.05 - 1	0.05 - 1	
K_{S}	d	Slow recession time scale	MRC*			