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Multi-decadal fluctuations in root zone storage capacity through vegetation adaptation to hydro-climatic variability have minor effects on the hydrological response in the Neckar River basin, Germany

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Table S1. Water balance and constitutive equations of distributed hydrological model

Reservoirs	Water balance		Constitutive equations	
Interception	$\frac{ds_i}{dt} = P_{rain} - E_i - P_{re}$	(S4)	$P_{rain} = P, when\ T > T_t$	(S10)
			$E_i = \min(E_p, S_i/dt)$	(S11)
			$P_{re} = \max((S_i - S_{imax})/dt, 0)$	(S12)
Snow	$\frac{ds_{snow}}{dt} = P_{snow} - M_{snow}$	(S5)	$P_{snow,e} = P, when\ T_e \leq T_t$	(S13)
			$P_{snow} = \sum P_{snow,e} \cdot W_e$	(S14)
			$M_{snow,e} = \min(C_{melt} * (T_e - T_t), S_{snow,e}/dt), when\ T_e > T_t$	(S15)
			$M_{snow} = \sum M_{snow,e} \cdot W_e$	(S16)
Unsaturated reservoir	Forest/ Grass: $\frac{ds_u}{dt} = P_e - E_a - R_u - R_{perc}$	(S6)	$P_e = P_{re} + M_{snow}$	(S17)
			$\rho = S_u/S_{umax}$	(S18)
			$E_a = (E_p - E_i) * \min(\rho/C_a, 1)$	(S19)
			$C_r = 1 - (1 - \rho)^{\gamma}$	(S20)
	Wetland: $\frac{ds_u}{dt} = P_e - E_a - R_u + R_{cap}$	(S7)	$R_u = (1 - C_r) * P_e$	(S21)
			$R_{perc} = \min(c_{pmax} * \rho, S_u/dt)$	(S22)
			$R_{cap} = \min(c_{pmax} * (1 - \rho), \frac{S_s}{dt} * P_{HRU})$	(S23)
			$R_{pref} = (1 - D) * R_u$	(S24)
Fast reservoir	$\frac{ds_f}{dt} = R_f - Q_f$	(S8)	Forest/ Grass: $R_f = D * R_u$	(S25)
			Wetland: $R_f = R_u$	(S26)
			$Q_f = K_f * S_f$	(S27)
Slow reservoir	$\frac{ds_s}{dt} = R_{perctot} + R_{preftot} - R_{captot} - Q_s$	(S9)	$R_{perctot} = \sum R_{perc} \cdot P_{HRU}$	(S28)
			$R_{preftot} = \sum R_{pref} \cdot P_{HRU}$	(S29)
			$R_{captot} = \sum R_{cap} \cdot P_{HRU}$	(S30)
			$Q_s = K_s * S_s$	(S31)

Table S2. Model parameters and their prior distributions in Borg_MOEA method.

	Parameters	Unit	Description	Parameter Constraints	Prior distributions	References
Global	T_t	°C	Threshold temperature to split snowfall and rainfall		-2.5-2.5	(Gao et al., 2014; Hrachowitz et al., 2013)
	C_{melt}	mm °C^{-1}	Melt factor		1-5	(Prenner et al., 2018)
	C_a	-	Evapotranspiration coefficient		0.1-0.7	(Gao et al., 2017)
	K_s	d^{-1}	Recession coefficient of slow response reservoir		0.002-0.2	(Prenner et al., 2018)
Forest	S_{imaxF}	mm	Interception capacity	S_{imaxF}>S_{imaxG}	0.1-5	(Gao et al., 2014)
	S_{umaxF}	mm	Root zone storage capacity	S_{umaxF}>S_{umaxG}	50-500	(Gao et al., 2014)
	γ_F	-	Shape parameter		0.1-5	(Gao et al., 2014)
	D	-	Splitter to fast and slow response reservoirs		0-1	(Gao et al., 2014)
	c_{pmaxF}	mm d^{-1}	Percolation capacity		0.1-4	(Prenner et al., 2018)
	K_{fF}	d^{-1}	Recession coefficient of fast response reservoir	K_{fF}>K_s	0.2-5	(Hrachowitz et al., 2013)
Grassland	S_{imaxG}	mm	Interception capacity		0.1-5	(Gao et al., 2014)
	S_{umaxG}	mm	Root zone storage capacity	S_{umaxG}>S_{umaxW}	50-500	(Gao et al., 2014)
	γ_G	-	Shape parameter		0.1-5	(Gao et al., 2014)
	c_{pmaxG}	mm d^{-1}	Percolation capacity		0.1-4	(Prenner et al., 2018)
	K_{fG}	d^{-1}	Recession coefficient of fast response reservoir	K_{fG}>K_s	0.2-5	(Hrachowitz et al., 2013)
Wetland	S_{umaxW}	mm	Root zone storage capacity	$S_{umaxW} < S_{umaxG}$	50-500	(Gao et al., 2014)
	γ_W	-	Shape parameter		0.1-5	(Gao et al., 2014)
	c_{rmax}	mm d^{-1}	Percolation capacity		0.1-4	(Gao et al., 2014)

Table S3. The prior parameter ranges and the ranges of the pareto optimal solutions from two calibration cases (Scenarios 1 – 2) are shown here.

Parameter	Prior range	Posterior distribution				
		Scenario 1	Scenario2			
		T (1953-2022)	t1 (1953-1972)	t2 (1973-1992)	t3 (1993-2012)	t4 (2013-2022)
T_t (°C)	-2.5-2.5	0.40(-0.80-0.64)	-0.08(-2.46-0.88)	-0.08(-2.19-0.97)	0.19(-1.31-1.69)	1.18(-1.42-2.49)
C_{melt} (mm°C^{-1}d^{-1})	1-5	4.46(3.14-4.87)	2.75(1.79-4.35)	1.77(1.29-4.55)	1.97(1.58-4.30)	3.08(1.24-3.95)
C_a (-)	0.1-0.7	0.66(0.43-0.68)	0.51(0.41-0.62)	0.60(0.49-0.67)	0.61(0.39-0.67)	0.67(0.42-0.63)
K_s (d^{-1})	0.002-0.2	0.03(0.02-0.07)	0.03(0.03-0.07)	0.05(0.03-0.15)	0.04(0.03-0.18)	0.03(0.01-0.05)
S_{imaxF} (mm)	0.1-5	1.55(1.55-2.87)	2.54(2.00-4.82)	2.43(1.93-4.76)	1.82(1.79-4.69)	3.03(1.75-3.82)
S_{umaxF} (mm)	50-200	158(138-167)	148(114-165)	149(130-174)	120(100-159)	125(122-169)
γ_F (-)	0.1-5	3.43(0.58-4.51)	1.02(1.02-4.18)	2.02(1.22-4.46)	0.69(0.39-4.14)	0.44(0.54-3.43)
D (-)	0-1	0.09(0.04-0.21)	0.06(0.01-0.43)	0.33(0.07-0.77)	0.41(0.10-0.72)	0.27(0.25-0.97)
C_{pmaxF} (mm d^{-1})	0.1-4	2.15(1.97-2.83)	1.83(0.53-2.53)	0.21(0.92-2.95)	0.92(0.91-3.47)	0.12(0.35-3.42)
K_{fF} (d^{-1})	0.2-5	0.41(1.48-3.19)	0.62(0.22-4.45)	0.30(0.30-4.94)	0.25(0.23-4.63)	0.53(0.21-3.95)
S_{imaxG} (mm)	0.1-5	0.97(0.70-1.30)	1.06(0.19-1.25)	1.24(0.44-1.50)	0.93(0.09-1.25)	0.41(0.01-1.02)
S_{umaxG} (mm)	50-200	94.6(71.4-123)	68.0(66.2-124)	115(88.5-123)	93.2(67.9-119)	102(86.4-141)
γ_G (-)	0.1-5	4.61(.033-4.34)	1.93(0.77-4.48)	0.87(0.11-1.89)	2.76(0.57-4.52)	4.58(0.62-4.04)
C_{pmaxG} (mm d^{-1})	0.1-4	0.87(0.87-3.37)	1.85(1.76-3.67)	3.14(2.83-3.78)	3.11(2.61-3.90)	2.62(1.66-3.96)
K_{fG} (d^{-1})	0.2-5	0.22(0.22-1.53)	0.23(0.21-2.12)	0.25(0.23-4.56)	0.23(0.23-4.98)	0.21(0.24-4.11)
S_{umaxW} (mm)	50-200	60.9(49.1-68.0)	55.0(27.2-69.0)	68.6(38.1-66.7)	51.3(20.3-58.9)	68.5(14.5-73.5)
γ_W (-)	0.1-5	0.35(0.14-2.40)	0.50(0.37-4.46)	3.84(0.22-4.65)	1.26(0.17-4.73)	0.63(0.09-3.66)
C_{rmax} (mm d^{-1})	0-4	1.05(0.76-2.17)	0.98(0.32-2.80)	1.13(0.41-2.11)	1.33(0.09-2.51)	0.03(2.34-3.76)

Table S4. The performance metrics for the most balanced solution (out of the backet) and the the 5^{th}-95^{th} percentile of all performance metrics (inside of the backet) for the full set of pareto optimal solutions for the multi-objective calibration cases (Scenarios 1 – 2) with $S_{umax,cal}$are shown here.

	Scenario 1					Scenario 2			
	T (1953-2022)	t1 (1953-1972)	t2 (1973-1992)	t3 (1993-2012)	t4 (2013-2022)	t1 (1953-1972)	t2 (1973-1992)	t3 (1993-2012)	t4 (2013-2022)
NSE_Q	0.59(0.06-0.55)	0.60(0.09-0.57)	0.58(0.07-0.55)	0.60(0.09-0.56)	0.57(0.11-0.53)	0.60(-0.16-0.57)	0.57(0.02-0.54)	0.59(-0.32-0.52)	0.56(-0.61-0.50)
$NSE_{log(Q)}$	0.67(0.34-0.64)	0.65(0.36-0.62)	0.68(0.37-0.65)	0.66(0.30-0.63)	0.70(0.32-0.66)	0.69(0.23-0.62)	0.65(0.30-0.59)	0.63(-0.33-0.53)	0.72(-0.77-0.66)
$NSE_{FDClog(Q)}$	0.96(0.92-0.99)	0.93(0.89-0.98)	0.95(0.90-0.99)	0.98(0.93-0.99)	0.97(0.91-098)	0.96(0.94-0.99)	0.98(0.88-0.99)	0.98(0.58-0.99)	0.97(0.16-0.99)
NSE_{Cr}	0.90(0.86-0.91)	0.86(0.84-0.88)	0.91(0.89-0.93)	0.90(0.88-0.92)	0.91(0.87-0.91)	0.86(0.84-0.89)	0.91(0.86-0.93)	0.90(0.87-0.92)	0.89(0.63-0.92)
NSE_{AC}	0.99(0.56-0.97)	0.94(0.45-0.96)	0.98(0.55-0.96)	0.98(0.62-0.98)	0.82(0.11-0.91)	0.98(0.21-0.94)	0.87(0.47-0.96)	0.95(0.27-0.94)	0.90(0.07-0.97)
$RE_{Cr,summer}$	0.83(0.82-0.89)	0.80(0.79-0.90)	0.83(0.81-0.90)	0.85(0.83-0.89)	0.85(0.83-0.87)	0.90(0.81-0.90)	0.89(0.79-0.90)	0.87(0.77-0.89)	0.84(0.69-0.88)
$RE_{Cr,winter}$	0.91(0.89-0.91)	0.89(0.87-0.89)	0.93(0.92-0.93)	0.91(0.89-0.91)	0.92(0.90-0.92)	0.88(0.88-0.90)	0.92(0.92-0.93)	0.90(0.89-0.91)	0.91(0.82-0.92)
DE	0.78(0.54-0.76)	0.77(0.53-0.76)	0.79(0.56-0.77)	0.79(0.55-0.77)	0.78(0.53-0.74)	0.79(0.39-0.76)	0.78(0.51-0.73)	0.78(0.27-0.72)	0.79(0.01-0.75)

Table S5. The performance metrics for the most balanced solution(out of the backet) and the the 5^{th}-95^{th} percentile of all performance metrics (inside of the backet) for two cases (Scenarios 1 – 2) with $S_{umax,WB}$ are shown here.

	Scenario 1					Scenario 2			
	T (1953-2022)	t1 (1953-1972)	t2 (1973-1992)	t3 (1993-2012)	t4 (2013-2022)	t1 (1953-1972)	t2 (1973-1992)	t3 (1993-2012)	t4 (2013-2022)
NSE_Q	0.59(0.06-0.55)	0.60(0.06-0.56)	0.58(0.03-0.54)	0.60(0.06-0.56)	0.56(0.09-0.53)	0.60(0.04-0.56)	0.58(0.06-0.55)	0.59(0.04-0.55)	0.56(0.08-0.53)
$NSE_{log(Q)}$	0.66(0.33-0.64)	0.64(0.34-0.62)	0.67(0.34-0.65)	0.65(0.28-0.63)	0.69(0.29-0.65)	0.64(0.33-0.61)	0.68(0.36-0.65)	0.64(0.25-0.62)	0.68(0.28-0.65)
$NSE_{FDClog(Q)}$	0.96(0.92-0.99)	0.94(0.89-0.98)	0.95(0.90-0.99)	0.98(0.93-0.99)	0.97(0.91-0.98)	0.94(0.90-0.98)	0.95(0.91-0.99)	0.98(0.93-0.99)	0.97(0.90-0.98)
NSE_{Cr}	0.89(0.87-0.91)	0.85(0.83-0.88)	0.91(0.88-0.93)	0.90(0.88-0.92)	0.91(0.87-0.91)	0.85(0.83-0.88)	0.91(0.89-0.93)	0.90(0.88-0.92)	0.91(0.87-0.91)
NSE_{AC}	0.98(0.60-0.97)	0.93(0.40-0.96)	0.98(0.56-0.96)	0.97(0.60-0.98)	0.84(0.16-0.91)	0.91(0.37-0.96)	0.98(0.53-0.96)	0.96(0.58-0.98)	0.85(0.21-0.92)
$RE_{Cr,summer}$	0.83(0.82-0.89)	0.80(0.79-0.89)	0.83(0.81-0.89)	0.84(0.83-0.89)	0.85(0.83-0.87)	0.80(0.78-0.89)	0.83(0.82-0.89)	0.84(0.83-0.89)	0.85(0.83-0.87)
$RE_{Cr,winter}$	0.91(0.90-0.91)	0.89(0.88-0.89)	0.93(0.92-0.93)	0.91(0.89-0.91)	0.92(0.90-0.92)	0.90(0.88-0.89)	0.93(0.92-0.93)	0.91(0.89-0.91)	0.92(0.90-0.92)
DE	0.78(0.54-0.76)	0.77(0.51-0.76)	0.78(0.54-0.76)	0.78(0.53-0.76)	0.78(0.52-0.75)	0.77(0.49-0.76)	0.79(0.55-0.77)	0.78(0.51-0.76)	0.77(0.52-0.75)

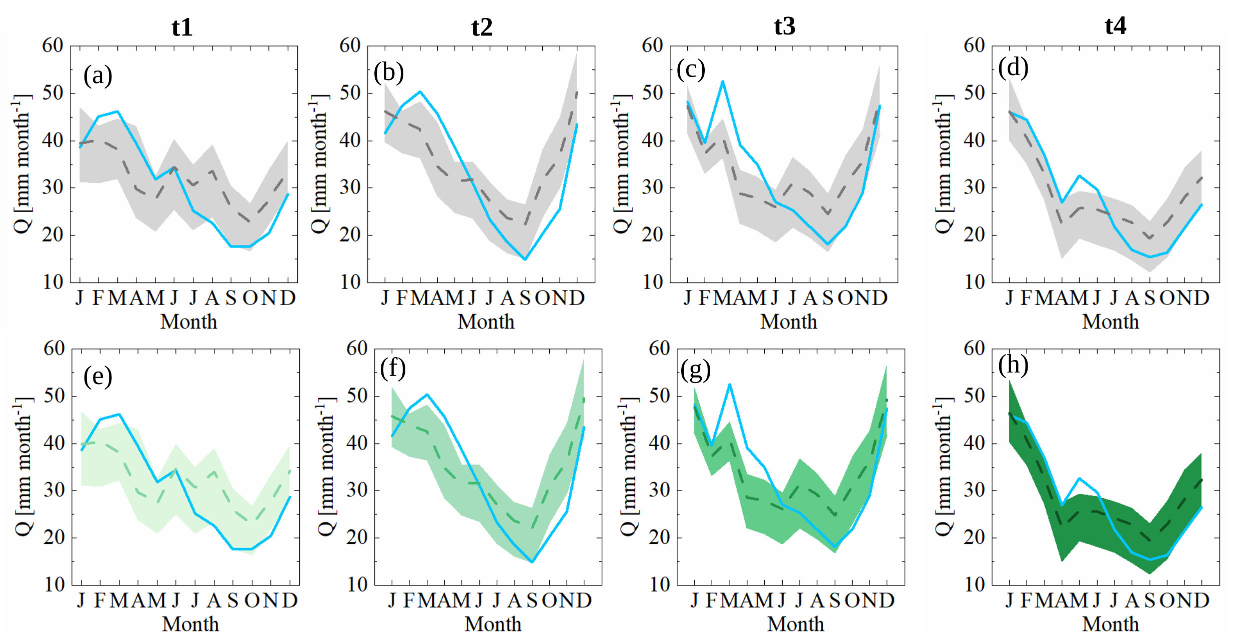

Figure S1. The mean monthly streamflow for four sub-time periods t_1-t_4 based on two scenarios ((a)-(d): scenario 1, (e)-(h): scenario 2). The blue lines indicate the observed streamflow. The dashed lines and shaded areas show the most balanced solution and 5th– 95th percentiles based on the pareto front solutions retained as feasible.

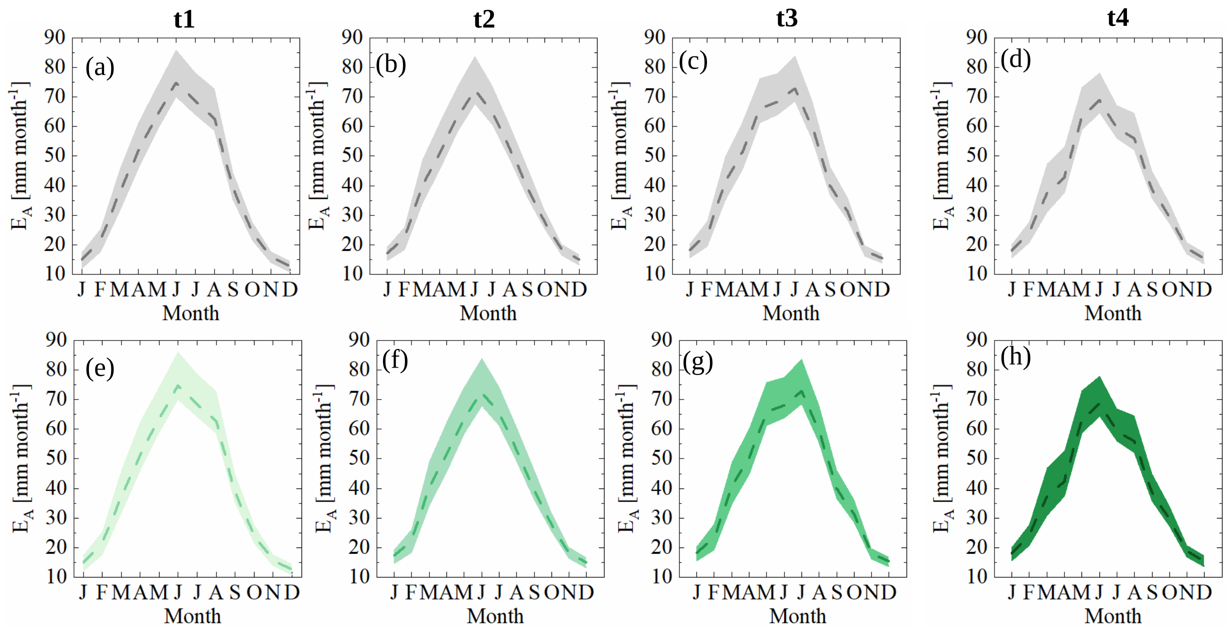

Figure S2. The mean monthly actual evaporation E_A for four sub-time periods t_1-t_4 based on two scenarios ((a)-(d): scenario 1, (e)-(h): scenario 2). The dashed lines and shaded areas show the most balanced solution and 5th– 95th percentiles based on the pareto front solutions retained as feasible.

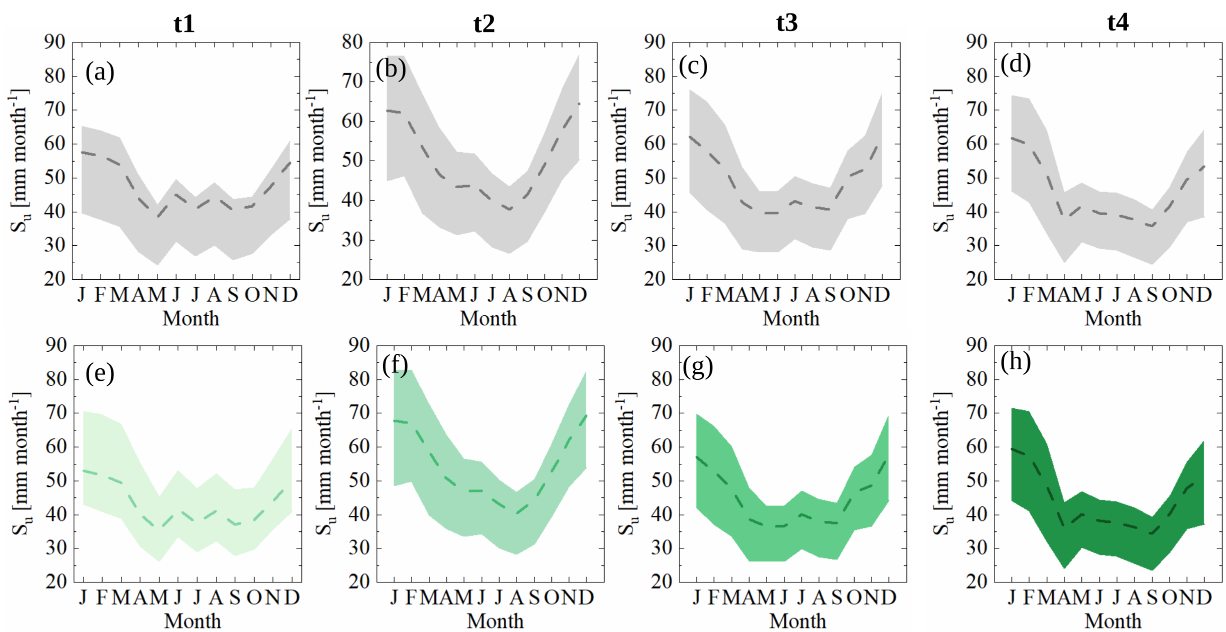

Figure S3. The mean monthly unsaturated zone storage S_u for four sub-time periods t_1-t_4 based on two scenarios ((a)-(d): scenario 1, (e)-(h): scenario 2). The dashed lines and shaded areas show the most balanced solution and 5th– 95th percentiles based on the pareto front solutions retained as feasible.

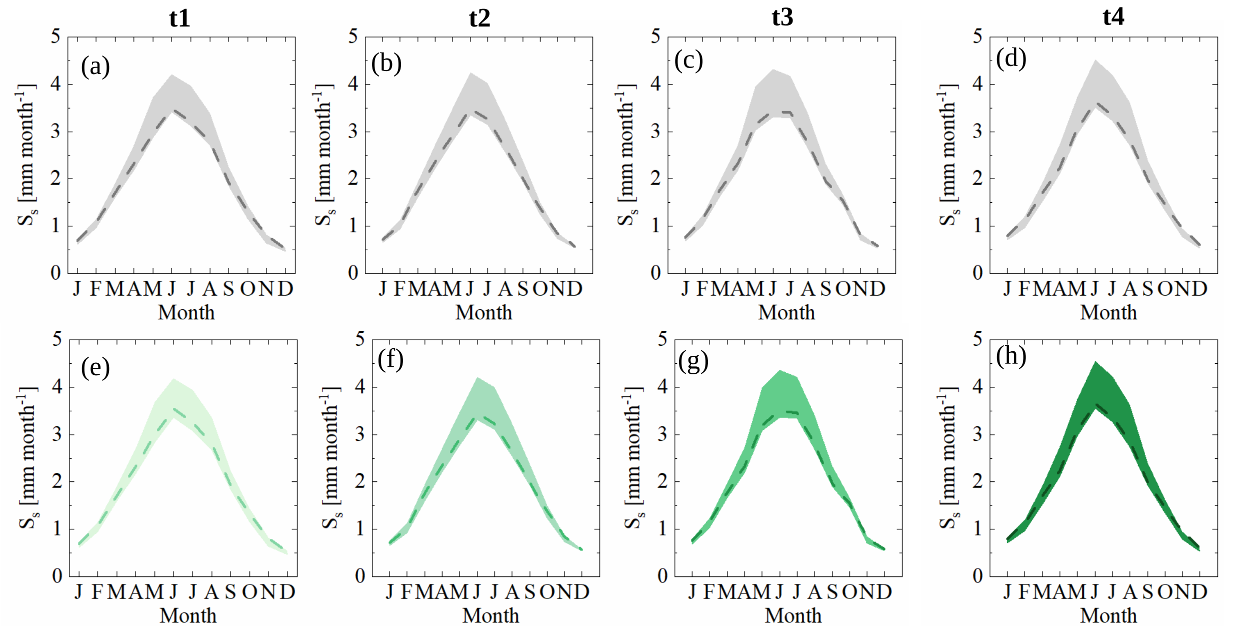

Figure S4. The mean monthly groundwater storage Ss (active storage) for four sub-time periods t_1-t_4 based on two scenarios ((a)-(d): scenario 1, (e)-(h): scenario 2). The dashed lines and shaded areas show the most balanced solution and 5th– 95th percentiles based on the pareto front solutions retained as feasible.

References

Gao, H., Ding, Y., Zhao, Q., Hrachowitz, M., and Savenije, H. H.: The importance of aspect for modelling the hydrological response in a glacier catchment in Central Asia, Hydrol. Process., 31, 2842-2859, https://doi.org/10.1002/hyp.11224, 2017.

Gao, H., Hrachowitz, M., Fenicia, F., Gharari, S., and Savenije, H.: Testing the realism of a topography-driven model (FLEX-Topo) in the nested catchments of the Upper Heihe, China, Hydrol. Earth Syst. Sci., 18, 1895-1915, https://doi.org/10.5194/hess-18-1895-2014, 2014.

Hrachowitz, M., Savenije, H., Bogaard, T., Tetzlaff, D., and Soulsby, C.: What can flux tracking teach us about water age distribution patterns and their temporal dynamics?, Hydrol. Earth Syst. Sci., 17, 533-564, https://doi.org/10.5194/hess-17-533-2013, 2013.

Hrachowitz, M., Stockinger, M., Coenders-Gerrits, M., van der Ent, R., Bogena, H., Lücke, A., and Stumpp, C.: Reduction of vegetation-accessible water storage capacity after deforestation affects catchment travel time distributions and increases young water fractions in a headwater catchment, Hydrol. Earth Syst. Sci., 25, 4887-4915, https://doi.org/10.5194/hess-25-4887-2021, 2021.

Prenner, D., Kaitna, R., Mostbauer, K., and Hrachowitz, M.: The value of using multiple hydrometeorological variables to predict temporal debris flow susceptibility in an alpine environment, Water Resour. Res., 54, 6822-6843, https://doi.org/10.1029/2018WR022985, 2018.