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Improved representation of soil moisture processes through incorporation of cosmic-ray neutron count measurements in a large-scale hydrologic model

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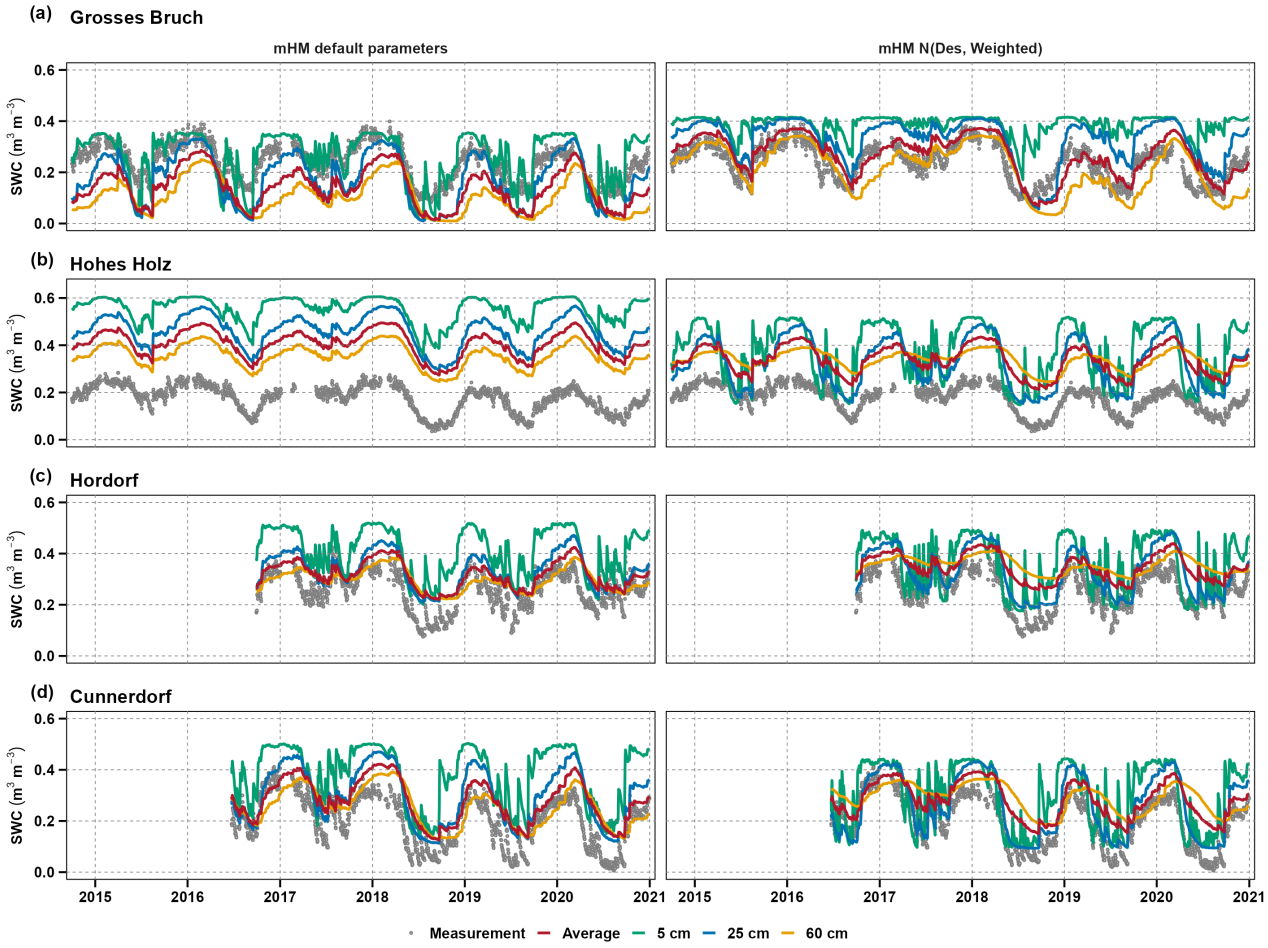

Figure S1. Soil water content at different land cover sites measured by the CRNS sensor network (dotted grey) and simulated by mHM at different depths (0–5 cm) in green, (0–25 cm) in blue, (0–60 cm) in yellow. The calibration is based on observed neutron counts for the $N_{\mathrm{Des,W}}$ method.

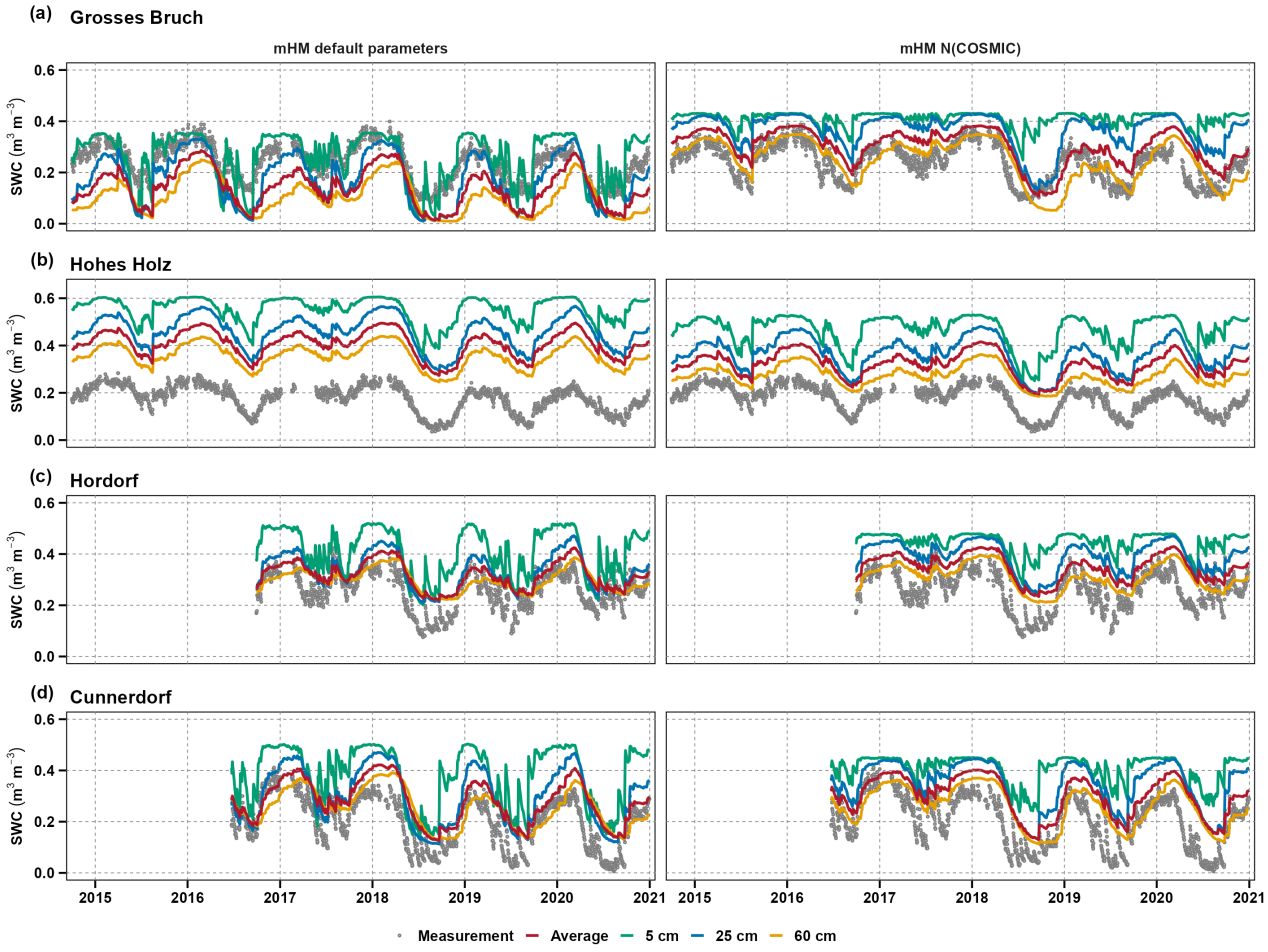

Figure S2. Soil water content at different land cover sites measured by the CRNS sensor network (dotted grey) and simulated by mHM at different depths (0–5 cm) in green, (0–25 cm) in blue, (0–60 cm) in yellow. The calibration is based on observed neutron counts for the N_{COSMIC} method.

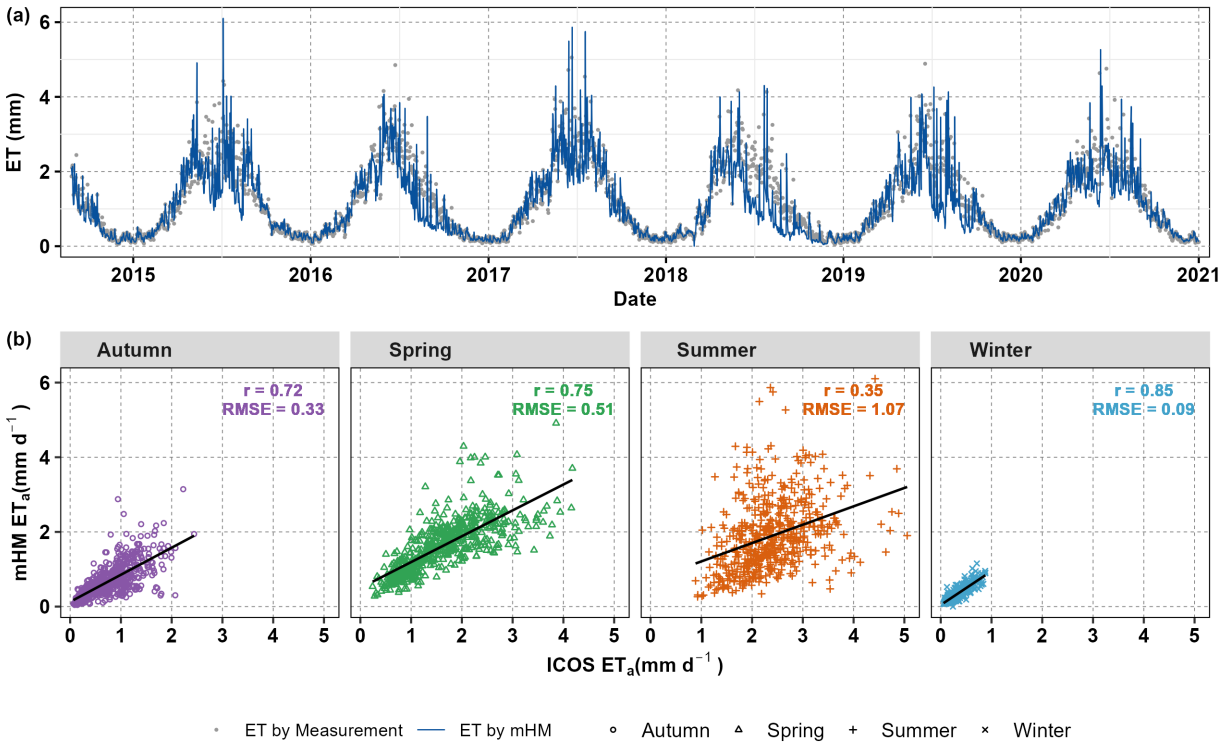

Figure S3. Correlations between observed and simulated evapotranspiration between different seasons. The correlation coefficients (r values) for each season are as follows: autumn [SON] (r = 0.79), spring [MAM] (r = 0.77), summer [JJA] (r = 0.42), and winter [DJF] (r = 0.87).

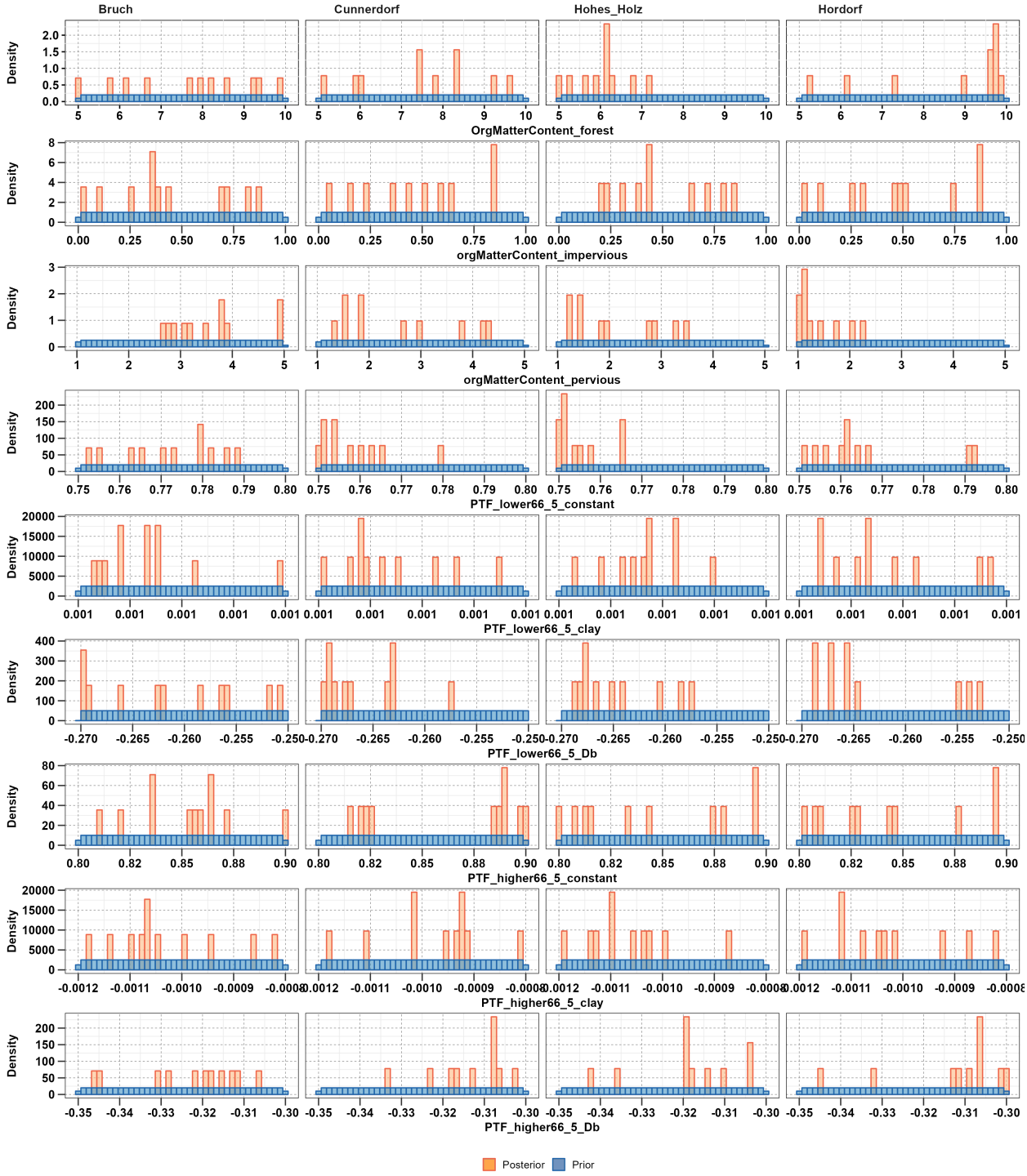

Figure S4. Probability Density Function (PDF) for nine parameters (soil moisture module) of the mHM taken from the three methods, namely $N_{\mathrm{Des,U}}$, $N_{\mathrm{Des,W}}$ and N_{COSMIC}(see Table 4). The prior PDF of the original sample, consisting of LHS 100 000 data points, is represented by the blue color. The behavioral PDF LHS 10, obtained after applying the objective function, is shown in orange for four sites

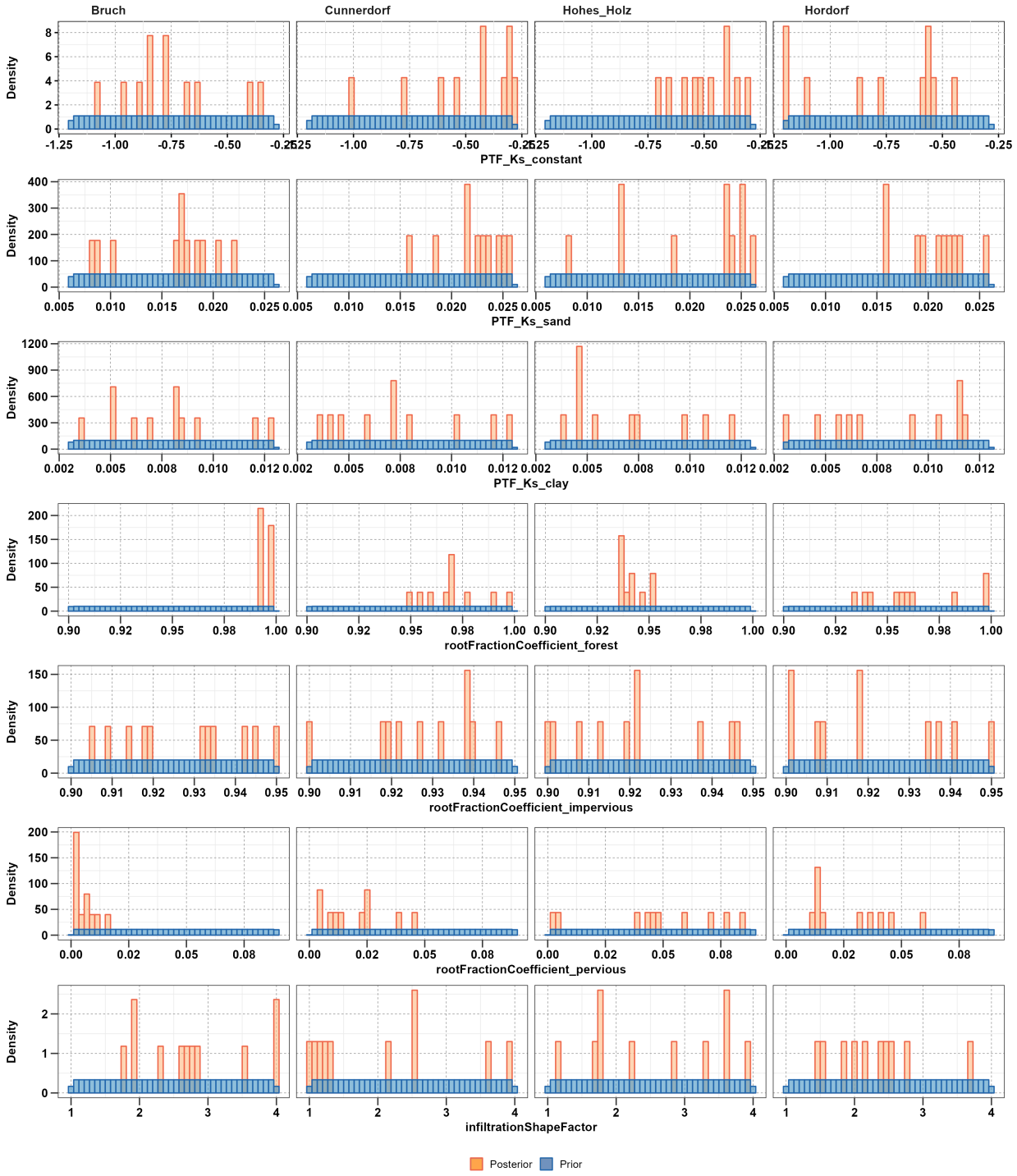

Figure S5. Probability Density Function (PDF) for seven parameters (soil moisture module) of the mHM taken from the three methods, namely $N_{\mathrm{Des,U}}$, $N_{\mathrm{Des,W}}$ and N_{COSMIC}(see Table 4). The prior PDF of the original sample, consisting of LHS 100 000 data points, is represented by the blue color. The behavioral PDF LHS 10, obtained after applying the objective function, is shown in orange for four sites.

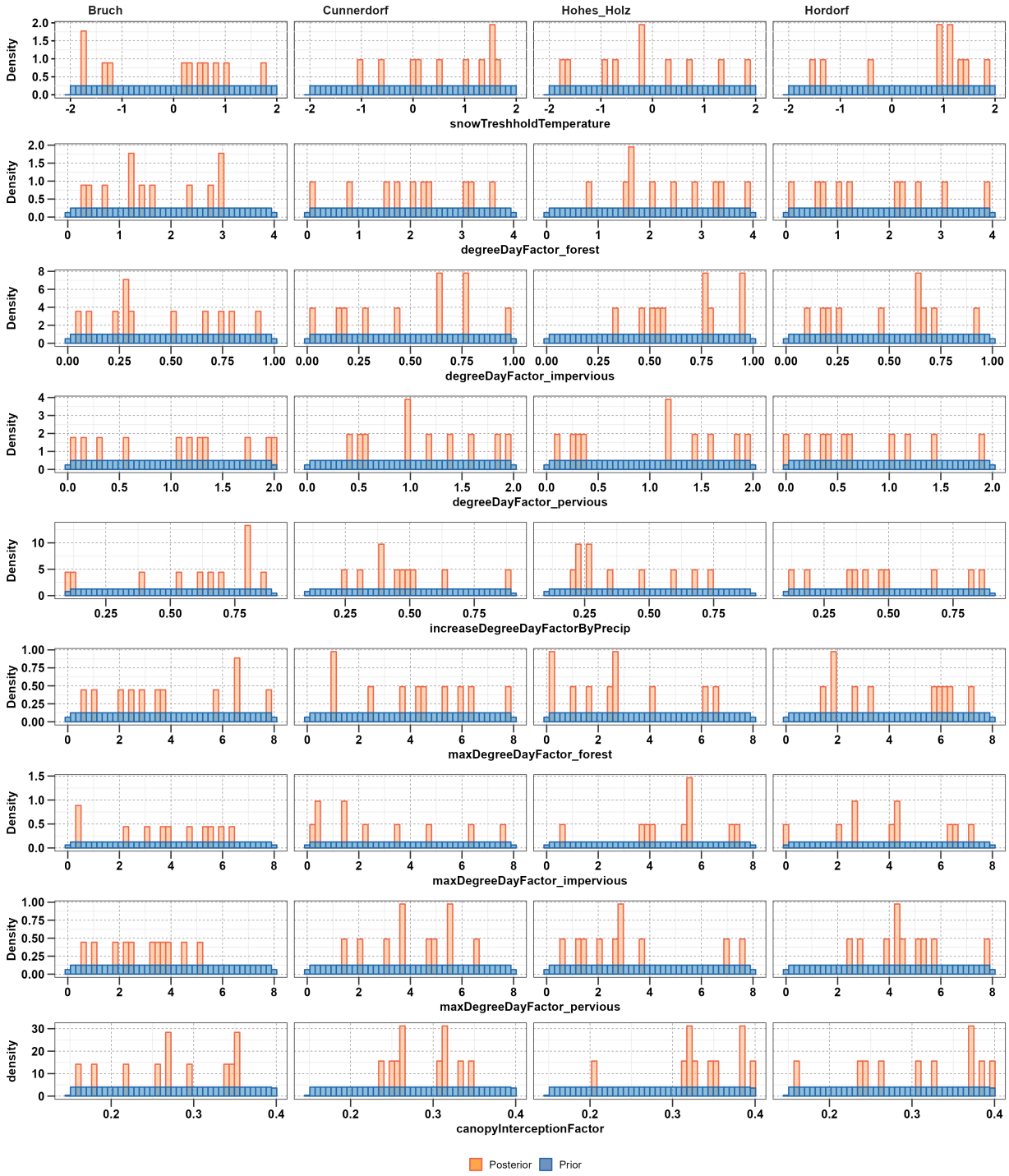

Figure S6. Probability Density Function (PDF) for nine parameters(snow module) of the mHM taken from the three methods, namely $N_{\mathrm{Des,U}}$, $N_{\mathrm{Des,W}}$ and N_{COSMIC}(see Table 4). The prior PDF of the original sample, consisting of LHS 100 000 data points, is represented by the blue color. The behavioral PDF LHS 10, obtained after applying the objective function, is shown in orange for four sites.

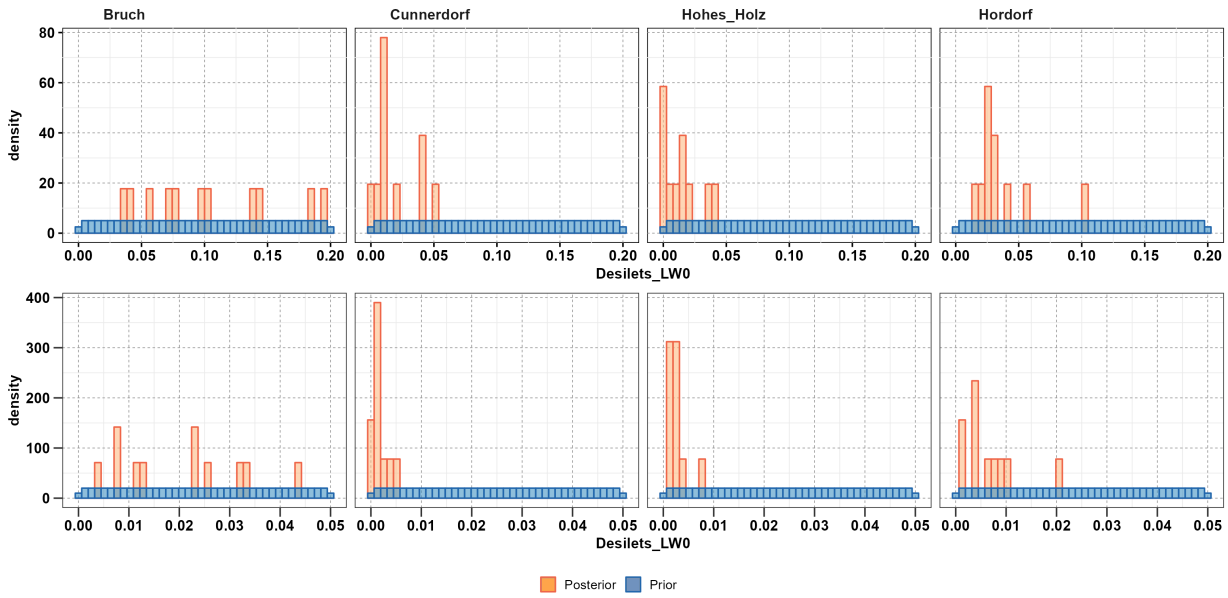

Figure S7. Probability Density Function (PDF) for six parameters (neutron module) of the mHM taken from the three methods, namely $N_{\mathrm{Des,U}}$, $N_{\mathrm{Des,W}}$ and N_{COSMIC}(see Table 4). The prior PDF of the original sample, consisting of LHS 100 000 data points, is represented by the blue color. The behavioral PDF LHS 10, obtained after applying the objective function, is shown in orange for four sites.

Table S1. Site-specific values for lattice water content ($\mathrm{cm^3 cm^{-3}}$), mean bulk density ($\mathrm{g\ cm^{-3}}$), and L_3 ($\mathrm{g\ cm^{-2}}$) are provided based on the best parameters obtained from three calibration methods ($N_{\mathrm{Des,U}}$, $N_{\mathrm{Des,W}}$, and N_{COSMIC}) across four different sites.

Sites		***Grosses Bruch***				***Hohes Holz***				***Hordorf***				***Cunnersdorf***			
Methods:	Symbol	Observed	$N_{\mathrm{Des,U}}$	$N_{\mathrm{Des,W}}$	N_{COSMIC}	Observed	$N_{\mathrm{Des,U}}$	$N_{\mathrm{Des,W}}$	N_{COSMIC}	Observed	$N_{\mathrm{Des,U}}$	$N_{\mathrm{Des,W}}$	N_{COSMIC}	Observed	$N_{\mathrm{Des,U}}$	$N_{\mathrm{Des,W}}$	N_{COSMIC}
Mean Bulk density ($\mathrm{gcm^{-3}}$)	ϱ	1.176	1.243	1.39	1.32	1.136	1.08	1.125	0.81	1.278	1.26	1.26	1.149	1.491	1.26	1.33	1.26
Lattice Water ($\mathrm{cm^3 cm^{-3}}$)	θ_{lw}	0.048	0.006	0.048	0.0461	0.038	0.0017	0.0057	0.027	0.043	0.028	0.043	0.033	0.030	0.0046	0.0025	0.0293
L_3 ($\mathrm{g\ cm^{-2}}$)	L_3	–	–	–	204.57	–	–	–	116.5	–		–	366.8	–	–	–	642.9

Table S2. Description of the mHM model parameters ranges used in this study.

Parameter	Description	Prior Range
	Interceptiont	
canintfact	canopyInterceptionFactor	0.15-0.4
	Snow	
tsnow	Threshold temperature for snow/rain (°C)	-2.0-2.0
degreeDayFactor_forest		0.0001-4.0
degreeDayFactor_impervious		0.00-1.0
degreeDayFactor_pervious		0.0-2.0
increaseDegreeDayFactorByPrecip	degree-day factor per unit of precip (mm day^1 °C^{-1})	0.1-0.9
maxDegreeDayFactor_forest		0.0-8.0
maxDegreeDayFactor_impervious		0.0-8.0
maxDegreeDayFactor_pervious		0.0-8.0
	Soil moisture	
orgmatforest	Organic matter content for forest	5.0-10.0
orgmatimper	Organic matter content for impervious zone	0.0-1.0
orgmatperv	Organic matter content for pervious zone	1.0-5.0
ptflowconst	ptf saturated water content: constant	0.75-0.8
ptflowclay	ptf saturated water content: coefficient clay content	0.0008-0.0012
ptflowdb	ptf saturated water content: coefficient bulk density	-0.27 - -0.25
pfthighconst	ptf saturated water content: constant	0.8-0.9
ptfhighclay	Coefficient for clay content in pedo-transfer function	-0.35-0.30
pfthighdb	Coefficient for bulk density in pedo-transfer function for soils	-0.0012-0.00080
ptfksconst	Constant in pedo-transfer function for hydraulic conductivity of soils	-1.200-0.285
ptfkssand	ptf hydraulic conductivity: coefficient sand content	0.006-0.026
pftksclay	ptf hydraulic conductivity: coefficient clay content	0.003-0.013
ptfksslp	Coefficient for slope in pedo-transfer function	60.96 - 60.96
rotfcoffore	Root fraction for forest areas	0.9- 0.999
rotfcofimperv		0.9-0.095
rotfcofpervi	Threshold for	0.001-0.090
infshapef	Infiltration shape factor	1.0 - 4.0
	neutron counts	
$N_{0(Des)}$	neutron intensity over dry soil under the same conditions (cph)	600 - 1500
$Desliets_{lw0}$	lattice water content gg^{-1}	0.0-0.2
$Desliets_{lw1}$	lattice water content gg^{-1}	0.0-0.05
$N_{0(COSMIC)}$	neutron intensity over dry soil under the same conditions (cph)	100-400
$COSMIC_{L30}$	calculated using mean soil bulk density g cm^{-2}	20.0-500.0
$COSMIC_{L31}$	calculated using mean soil bulk density g cm^{-2}	-120.0-200.0
$COSMIC_{lw0}$	lattice water content gg^{-1}	0.0-0.20
$COSMIC_{lw1}$	lattice water content gg^{-1}	0.0-0.05

Table S3. Description of the best parameter values in mHM for each site and methods i.e., *Grosses Bruch*, *Hohes Holz*, *Hordorf*, and *Cunnersdorf*. To better assist the user we keep the model nomenclature name the same as that is there in the model code mHM.

Parameters	***Grosses Bruch***			***Hohes Holz***			***Hordorf***			***Cunnersdorf***		
Methods:	$N_{Des,U}$	$N_{Des,W}$	N_{COSMIC}	$N_{Des,U}$	$N_{Des,W}$	N_{COSMIC}	$N_{Des,U}$	$N_{Des,W}$	N_{COSMIC}	$N_{Des,U}$	$N_{Des,W}$	N_{COSMIC}
Interception												
canintfact	0.26963375	0.39467625	0.27247125	0.38314375	0.28744375	0.17899125	0.38668875	0.24691125	0.33618375	0.26136875	0.39274875	0.20255125
Snow												
tsnow	-1.72058	-0.24602	-0.07114	-0.90398	-1.27014	-1.98074	-1.50122	-1.80374	0.92082	1.35414	-1.8023	0.62986
DDF_forest	1.181170473	2.362260945	1.427604312	1.640758983	3.659028525	3.598350042	1.0360941	2.687172822	2.924166897	2.257903554	1.513002177	2.365420866
DDF_impervious	0.231765	0.984535	0.554015	0.767975	0.802375	0.843145	0.650345	0.442805	0.445115	0.763965	0.714765	0.638455
DDF_pervious	1.98081	0.70283	0.35491	0.31141	1.94923	0.04935	0.40997	0.11735	1.61139	1.84961	0.11505	1.40673
increaseDDFByPrecip	0.801436	0.519148	0.405388	0.275668	0.277572	0.508308	0.49598	0.437388	0.312116	0.640156	0.3651	0.271764
maxDDF_forest	2.5606	3.65044	3.79716	2.69636	6.86284	2.88204	6.09524	5.83868	6.685	5.30796	2.22876	7.5542
maxDDF_impervious	5.54556	1.67764	0.4466	4.18084	5.22028	4.9406	2.1406	7.40588	3.3662	3.5006	2.705	1.63236
maxDDF_pervious	2.25852	0.91556	3.09588	3.67436	7.2938	3.92884	2.87644	4.14396	0.30396	6.49708	6.73188	5.09484
Soil moisture												
orgmatforest	7.920325	8.546725	8.149575	6.742125	5.108675	7.725625	6.102525	6.936725	8.819175	9.170475	9.270475	5.363775
orgmatimper	0.253925	0.619025	0.261195	0.835905	0.659235	0.196675	0.489835	0.853425	0.529195	0.154815	0.343535	0.589065
orgmatperv	4.9017	1.16946	1.09146	1.3969	1.14262	4.20494	1.11418	1.10058	2.11426	2.99006	1.27978	1.02526
ptflowconst	0.77919125	0.75686675	0.76741925	0.75156525	0.77374225	0.79731425	0.76049825	0.75274975	0.75735525	0.75352225	0.76110875	0.75536025
ptflowclay	0.000954942	0.001031974	0.000856918	0.001102182	0.001130958	0.00088389	0.000929002	0.000865138	0.000822562	0.000865258	0.000809874	0.001190426
ptflowdb	-0.2558197	-0.2556907	-0.2623517	-0.2685499	-0.2686231	-0.2519565	-0.2673095	-0.2660045	-0.2542747	-0.2689919	-0.2680209	-0.2616759
pfthighconst	0.8113785	0.8554075	0.8281195	0.8754505	0.8345925	0.8587685	0.8954385	0.8777155	0.8175895	0.8988685	0.8921375	0.8971475
ptfhighclay	-0.000817446	-0.000983926	-0.000935938	-0.000872634	-0.00084891	-0.000915346	-0.000870074	-0.001023514	-0.00118727	-0.000922102	-0.001042454	-0.00084843
pfthighdb	-0.31753025	-0.32982925	-0.30609325	-0.31914975	-0.33722325	-0.31565925	-0.30634375	-0.31458025	-0.33416625	-0.30712125	-0.34471675	-0.30714625
ptfksconst	-0.837774375	-1.041865125	-0.766367775	-0.394173225	-0.773385825	-0.488665275	-0.590413275	-0.681995625	-0.625192425	-0.421851975	-0.412345125	-0.372432825
ptfkssand	0.0104653	0.0202651	0.0164579	0.0132421	0.0089341	0.0167191	0.0226337	0.0149783	0.0210209	0.0245547	0.0183797	0.0082893
pftksclay	0.01272895	0.00321305	0.00582305	0.00967325	0.01108895	0.00506275	0.01157005	0.01098215	0.00754655	0.00596215	0.00332055	0.01272805
ptfksslp	60.96	60.96	60.96	60.96	60.96	60.96	60.96	60.96	60.96	60.96	60.96	60.96
rotfcoffore	0.998641125	0.994367295	0.998943075	0.935941455	0.907272045	0.972914985	0.958884705	0.953256555	0.997679835	0.968378805	0.962550675	0.991738845
rotfcofimperv	0.94968525	0.92632575	0.92657825	0.90099175	0.90925125	0.92889275	0.91826025	0.94530775	0.92371575	0.93860525	0.92961175	0.91830075
rotfcofpervi	0.010300055	0.001555805	0.001060075	0.059349735	0.038747125	0.063506035	0.013406155	0.068419725	0.001527325	0.012726195	0.040447025	0.001202475
infshapef	2.859955	2.516215	2.773645	1.792765	1.383535	3.322555	2.482105	1.123555	1.105975	1.007065	1.581325	3.708625
neutron counts												
$Desliets_{lw0}$	0.034847	0.109691		0.000731	0.024589		0.031221	0.039585		0.018199	0.010511	
$Desliets_{lw1}$	0.00342175	0.03951425		0.00161625	0.00205875		0.02101825	0.03462075		0.00155525	0.00125075	
$COSMIC_{L30}$			205.198375			243.065375			344.667875			488.996625
$COSMIC_{L31}$			65.0795			81.6965			29.3465			-26.5405
$COSMIC_{lw0}$			0.100185			0.087727			0.094789			0.083819
$COSMIC_{lw1}$			0.04364675			0.01504775			0.01345875			0.01718075