Supporting Material for
A snow and glacier hydrological model for large catchments - case study for the Naryn River, Central Asia.

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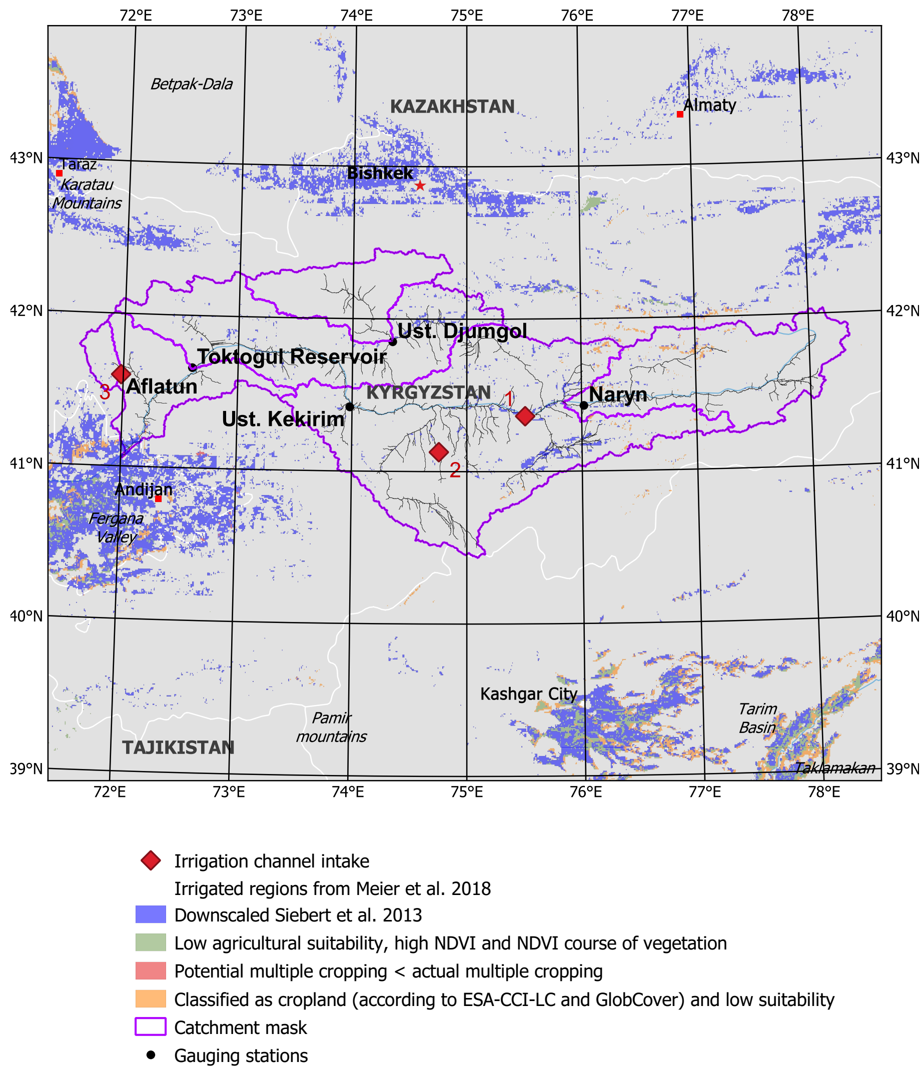

Figure S1. 30 arc-second irrigated areas in the Naryn catchment from (Meier et al., 2018). The locations of monthly observed flow intake to irrigation channels from the Central Asian Waterinfo Database are shown in 1. Kulanak, 2. Old Chegirtke and 3. Aflatun.

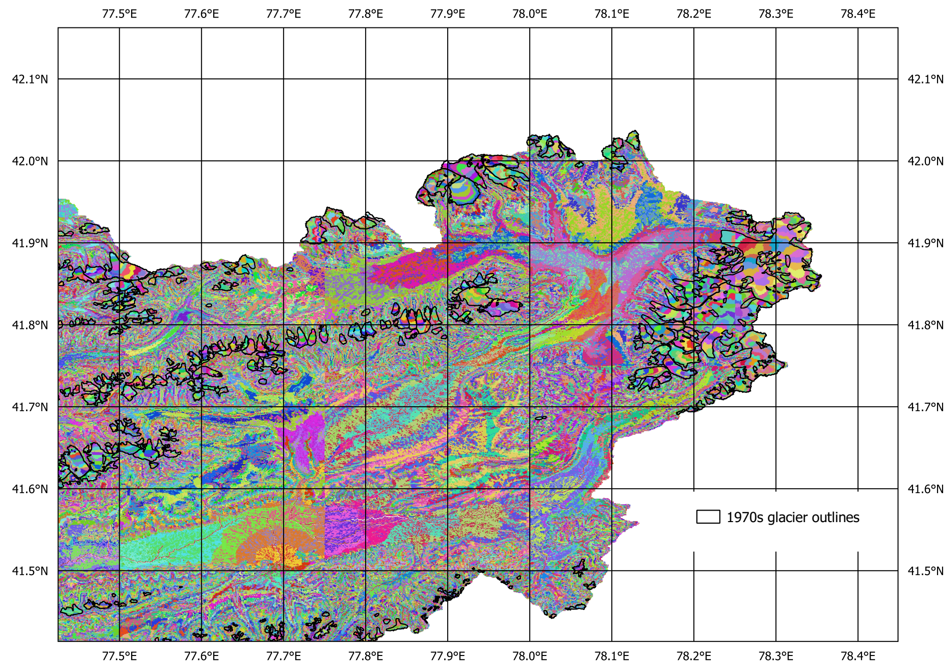

Figure S2. The spatial distribution of HRUs in the upper part of the Naryn catchment, where each colour denotes a unique HRU.

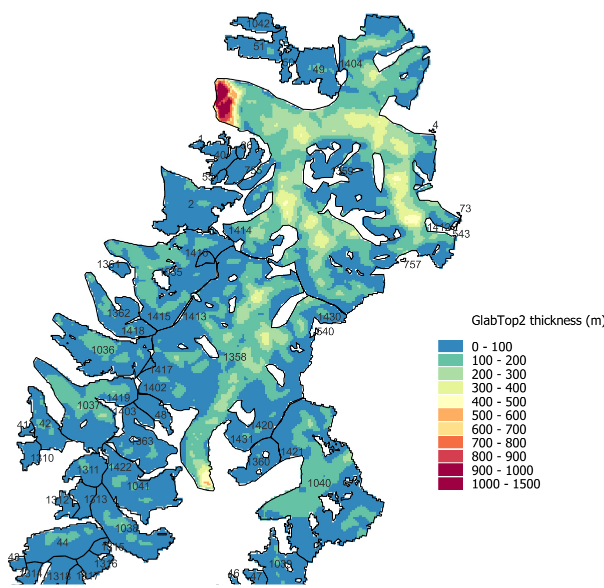

Figure S3. GlabTop2 ice thickness calculated for the 1970s using Landsat glacier outlines (Kriegel et al., 2013).

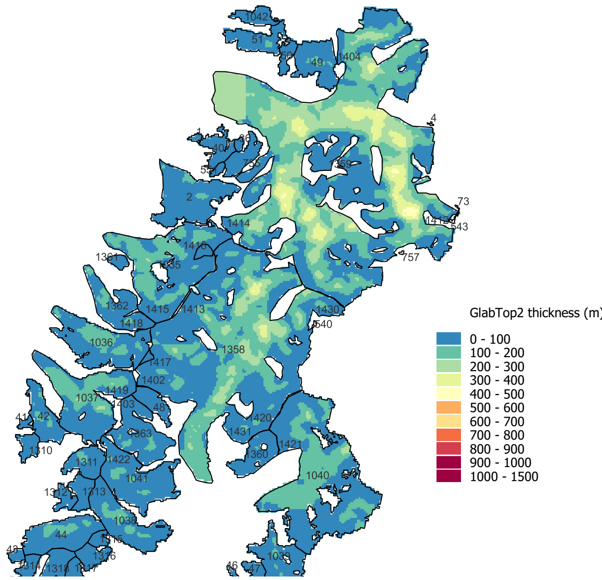

Figure S4. GlabTop2 ice thickness calculated for the 1970s using Landsat glacier outlines (Kriegel et al., 2013). A correction has been made to the thickness at the terminus of Petrov glacier number 1429 and glacier number 1358.

References

Kriegel, D., Mayer, C., Hagg, W., Vorogushyn, S., Duethmann, D., Gafurov, A., and Farinotti, D.: Changes in glacierisation, climate and runoff in the second half of the 20th century in the Naryn basin, Central Asia, Global and Planetary Change, 110, 51–61, https://doi.org/10.1016/j.gloplacha.2013.05.014, <GotoISI>://WOS:000329333200005, 2013.

Meier, J., Zabel, F., and Mauser, W.: A global approach to estimate irrigated areas – a comparison between different data and statistics, Hydrology and Earth System Sciences, 22, 1119–1133, https://doi.org/10.5194/hess-22-1119-2018, https://hess.copernicus.org/articles/22/1119/2018/, 2018.

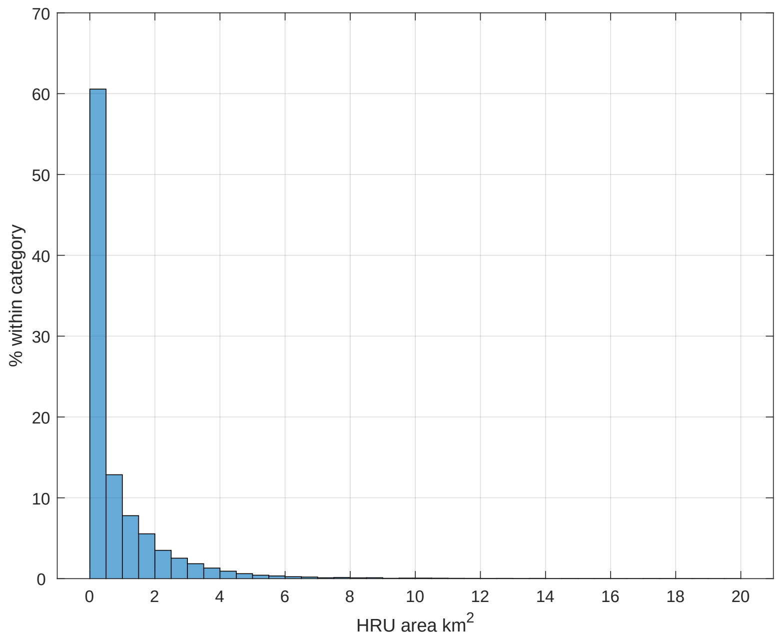

Figure S5. Histogram of Hydrologic Response Unit (HRU) areas in the Naryn River catchment. Approximately 60% of the catchment is covered in HRUs with an area between 0-500m^2

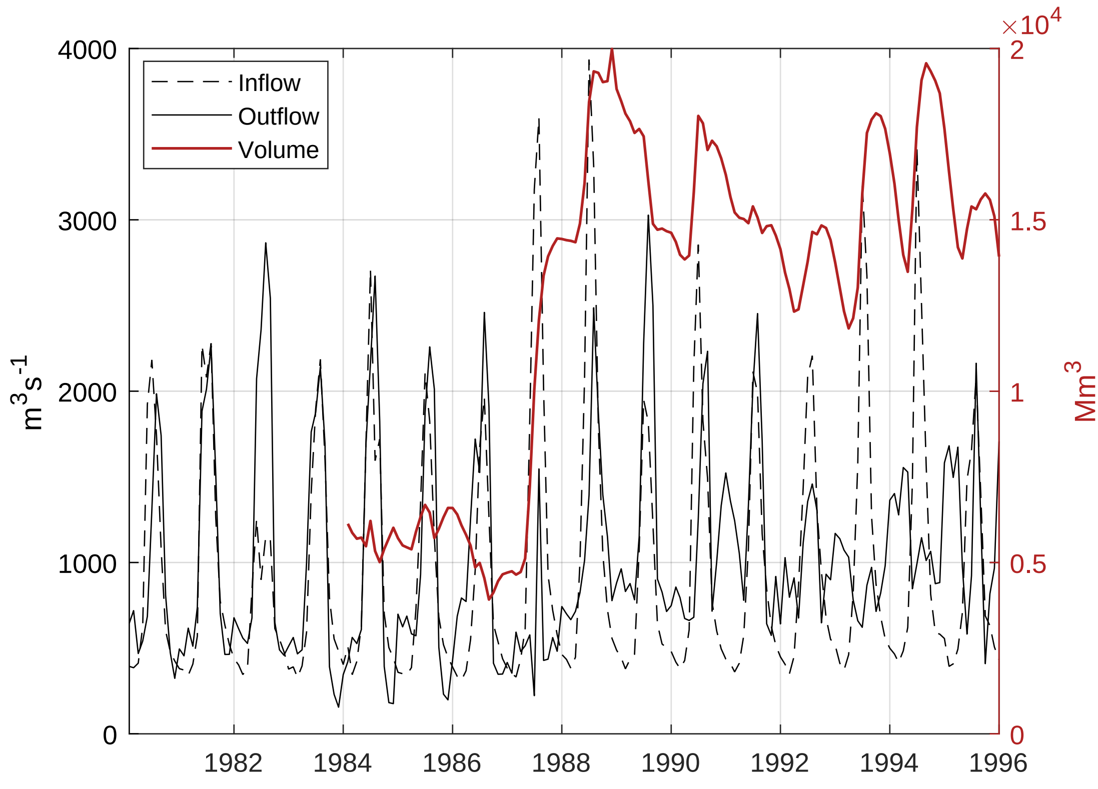

Figure S6. Monthly observations of Toktogul reservoir inflow, release and storage volume from the Central Asian Waterinfo Database.

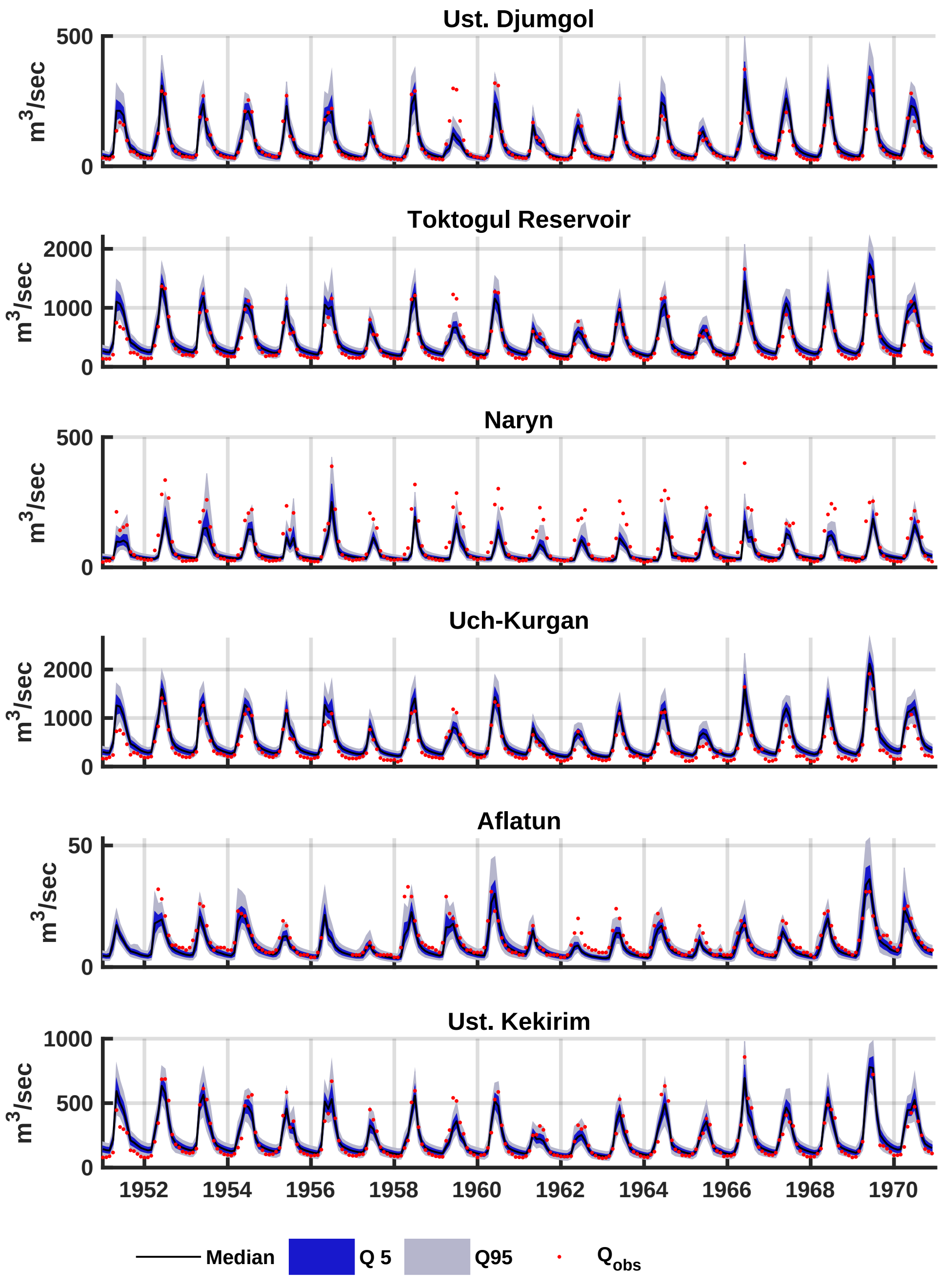

Figure S7. Observed and simulated discharge for the calibration period. Shown are the top 0.5% of experiments when the multi-site calibration approach is used. The shading shows the uncertainty bounds for the 5^{th} and 95^{th} percentiles and the black lines show the median (50^{th}

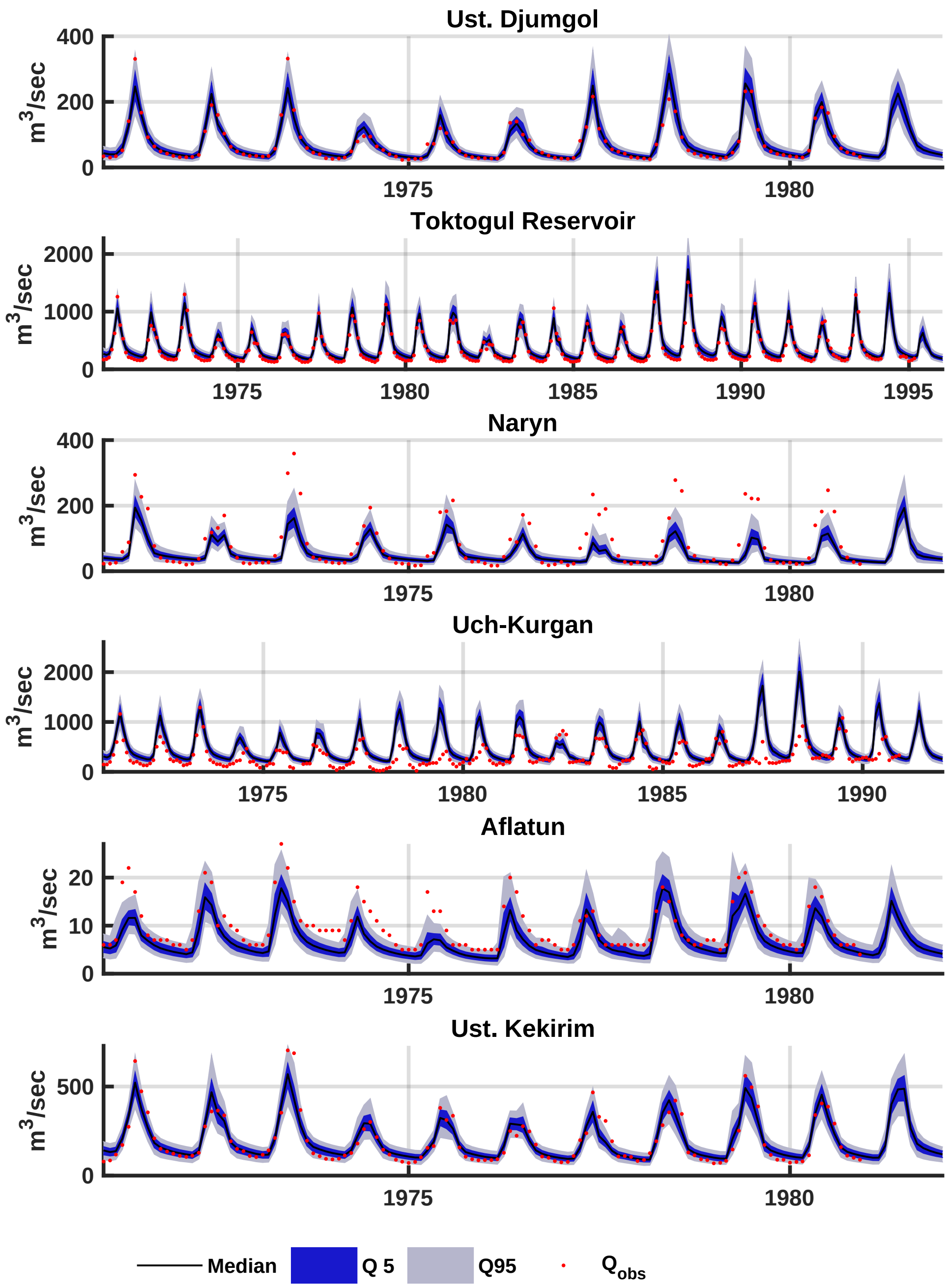

Figure S8. Observed and simulated discharge for the validation period. Shown are the top 0.5% of experiments when the multi-site calibration approach is used. The shading shows the uncertainty bounds for the 5^{th} and 95^{th} percentiles and the black lines show the median (50^{th}

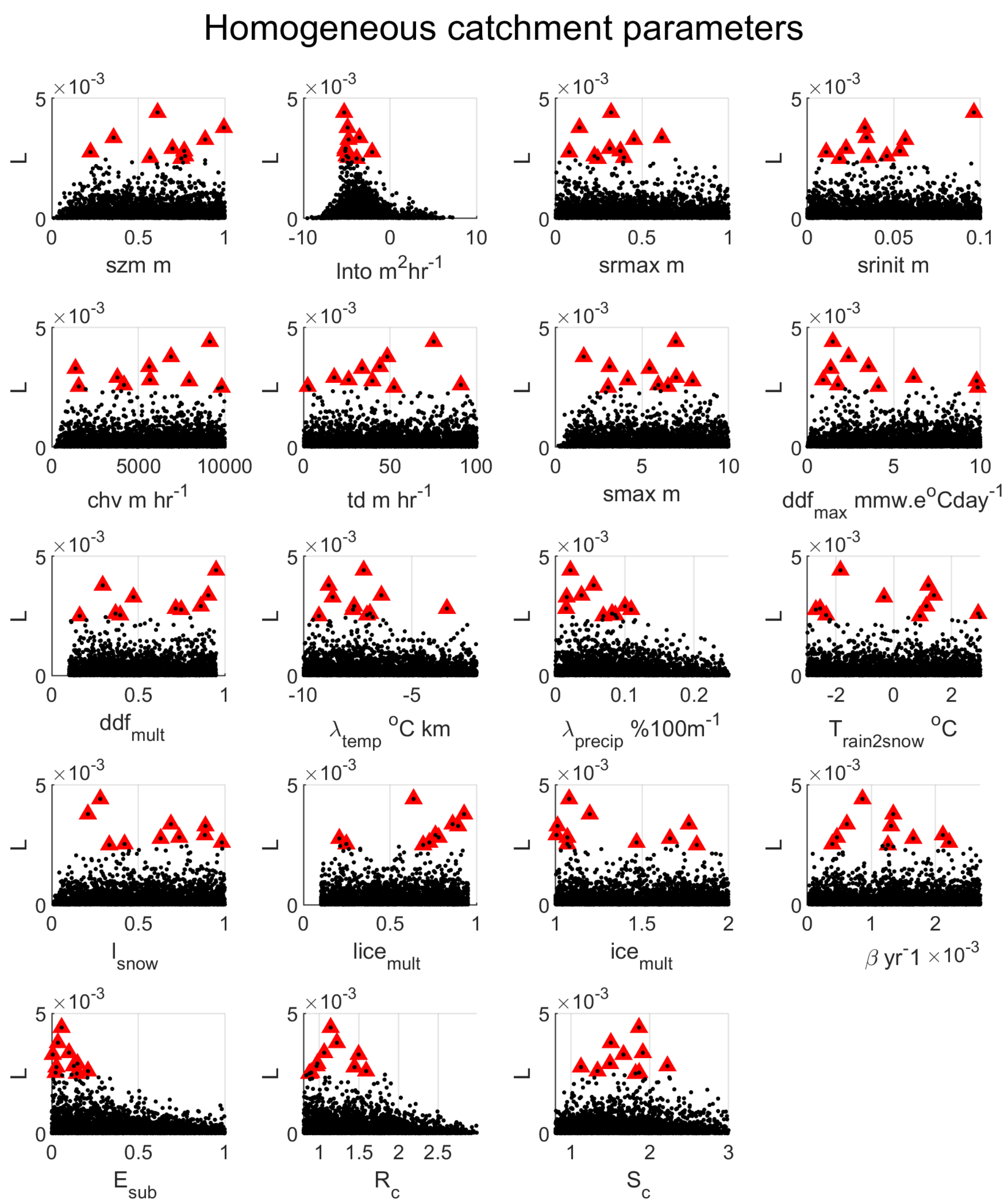

Figure S9. Dotty plots showing the conditional probability values when multi-site calibration is used. The black dots show the conditional probability for the best 5000 parameters, red triangles show the best conditional probability for the best 10 simulations.

Ust. Djumgol

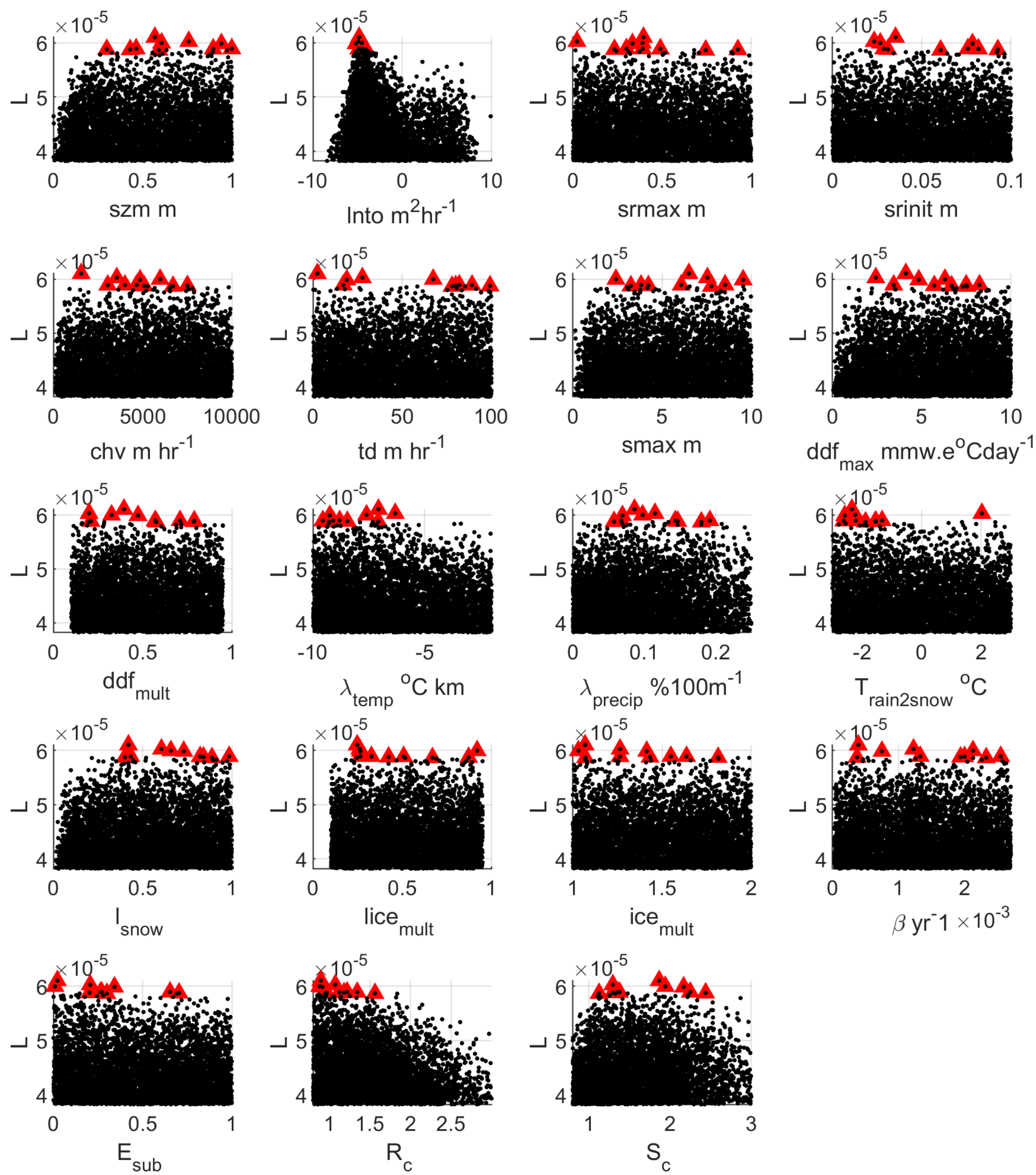

Figure S10. Dotty plots showing conditional probability values for the Ust. Djumgol catchment. The black dots show the conditional probability for the best 5000 parameters and red triangles show the conditional probability values for the best 10 simulations.

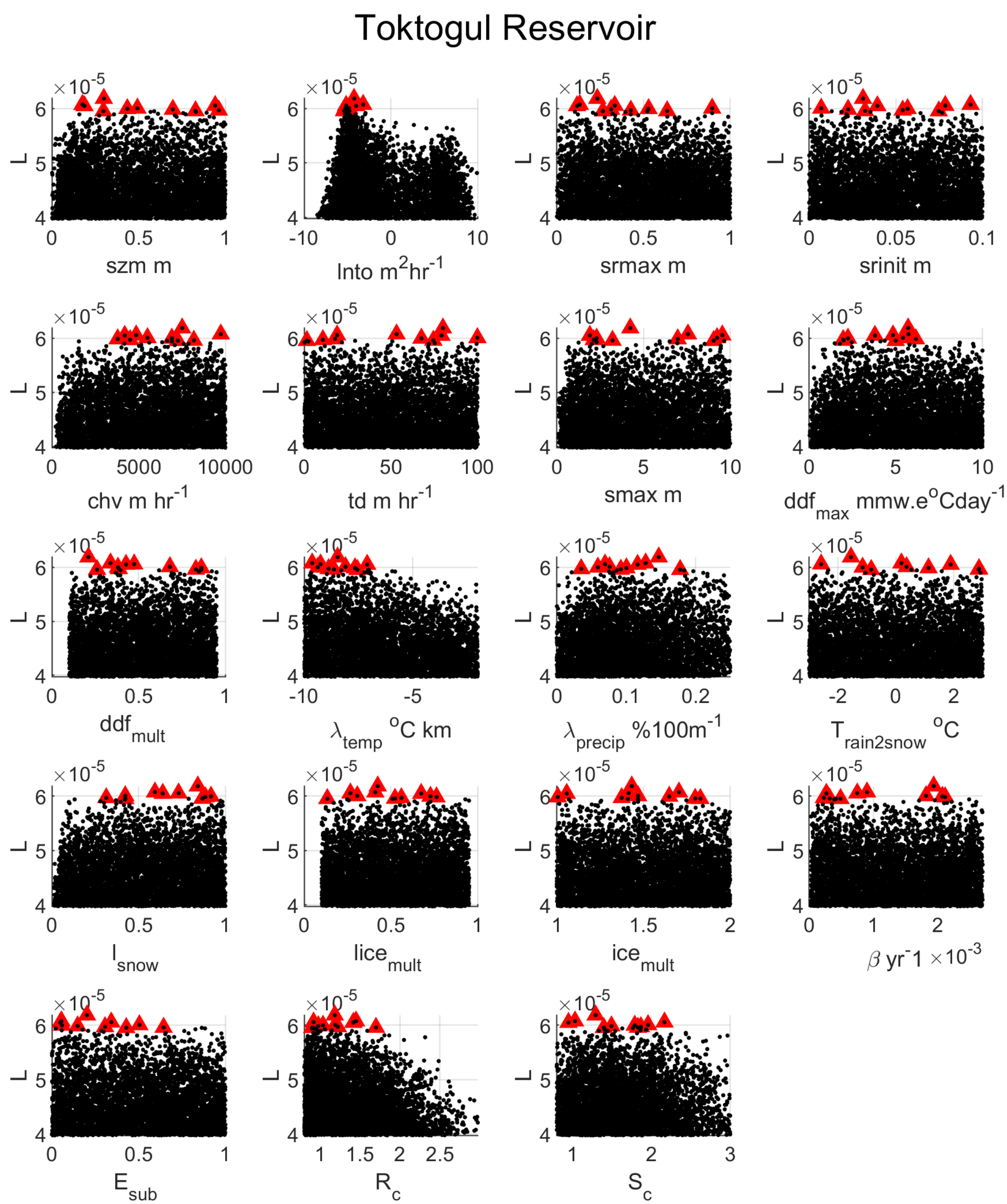

Figure S11. Dotty plots showing conditional probability values for the Toktogul Reservoir catchment. The black dots show the conditional probability for the best 5000 parameters and red triangles show the conditional probability values for the best 10 simulations.

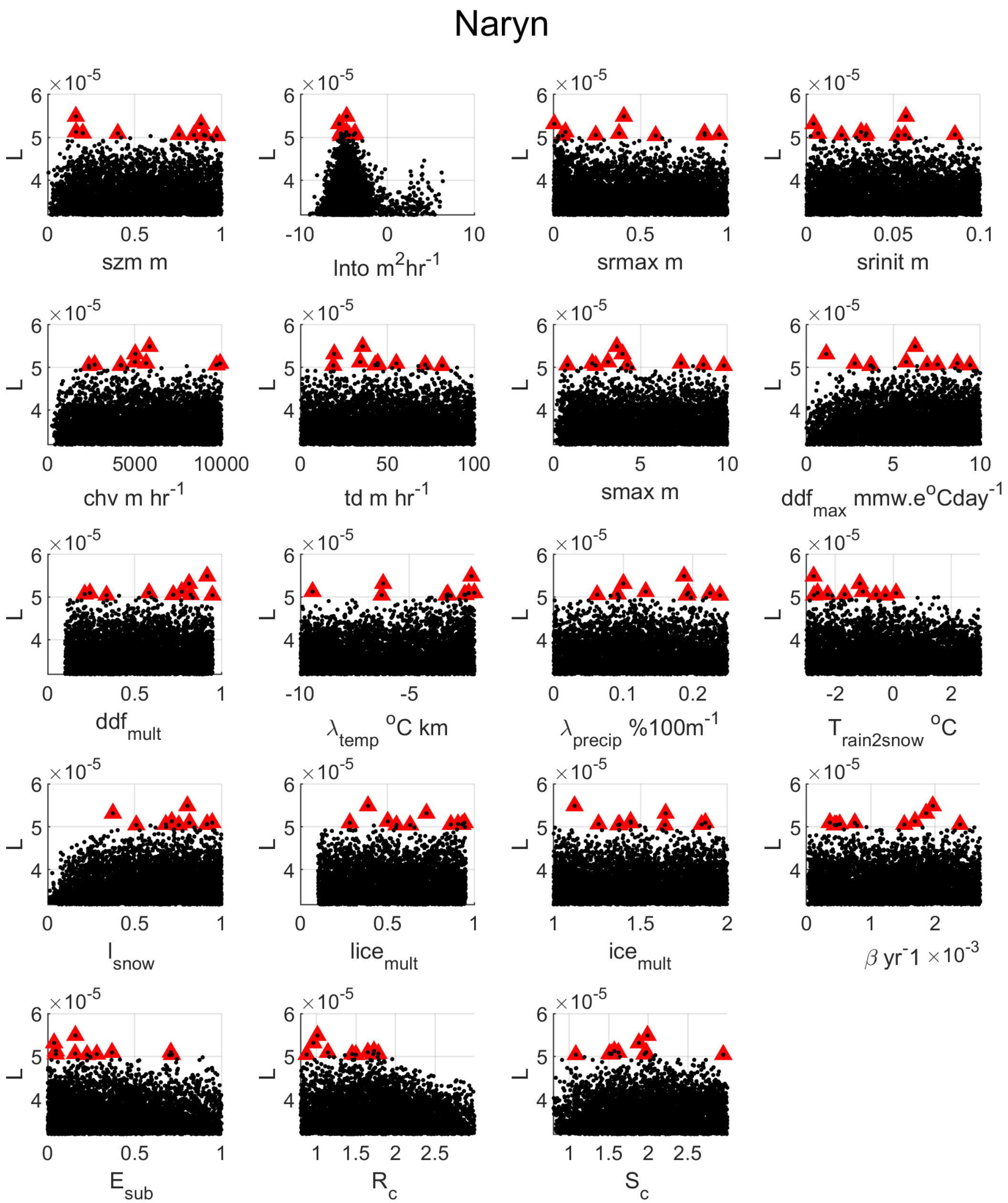

Figure S12. Dotty plots showing conditional probability values for the Naryn catchment. The black dots show the conditional probability for the best 5000 parameters and red triangles show the conditional probability values for the best 10 simulations.

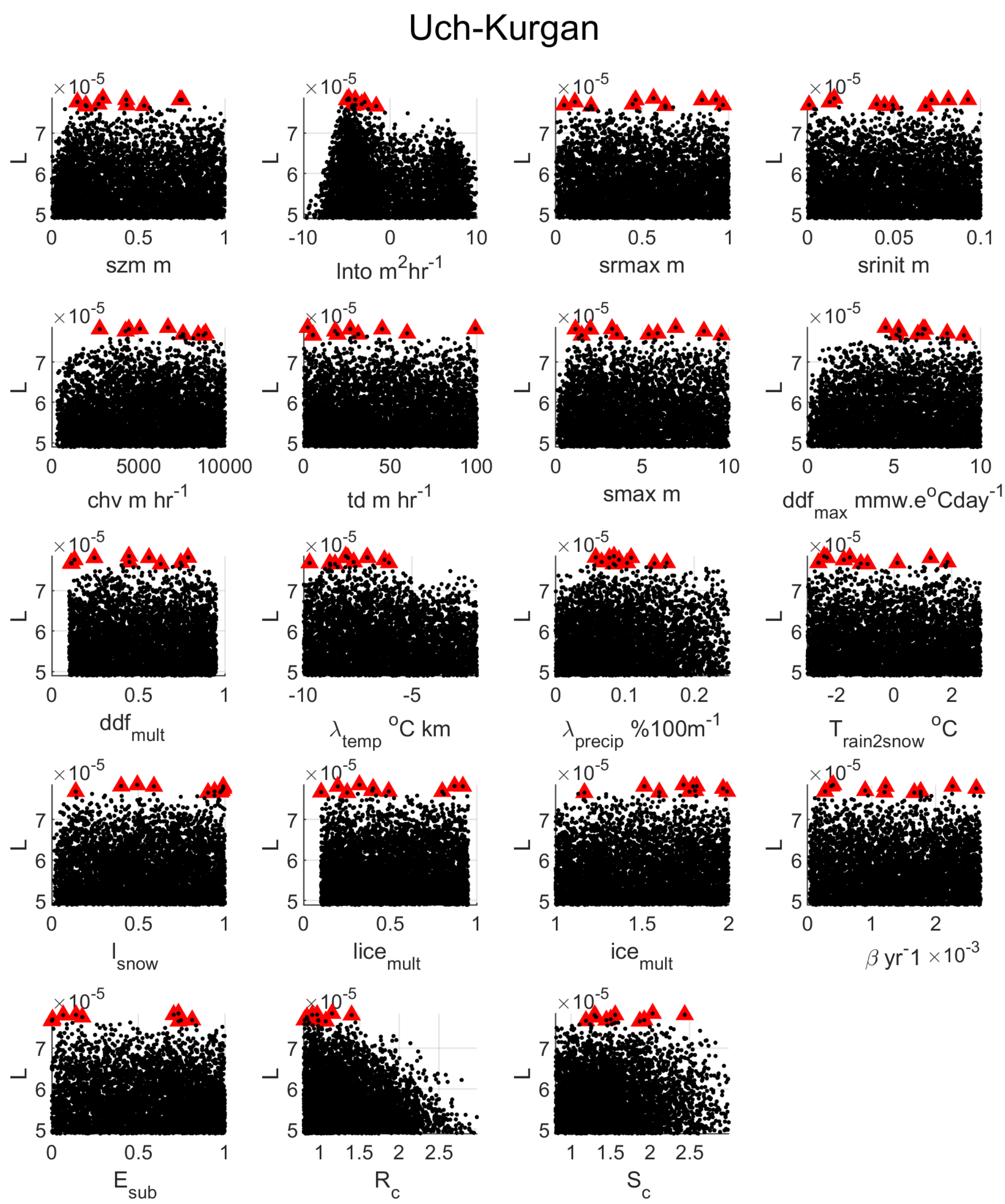

Figure S13. Dotty plots showing conditional probability values for the Uch-Kurgan catchment. The black dots show the conditional probability for the best 5000 parameters and red triangles show the conditional probability values for the best 10 simulations.

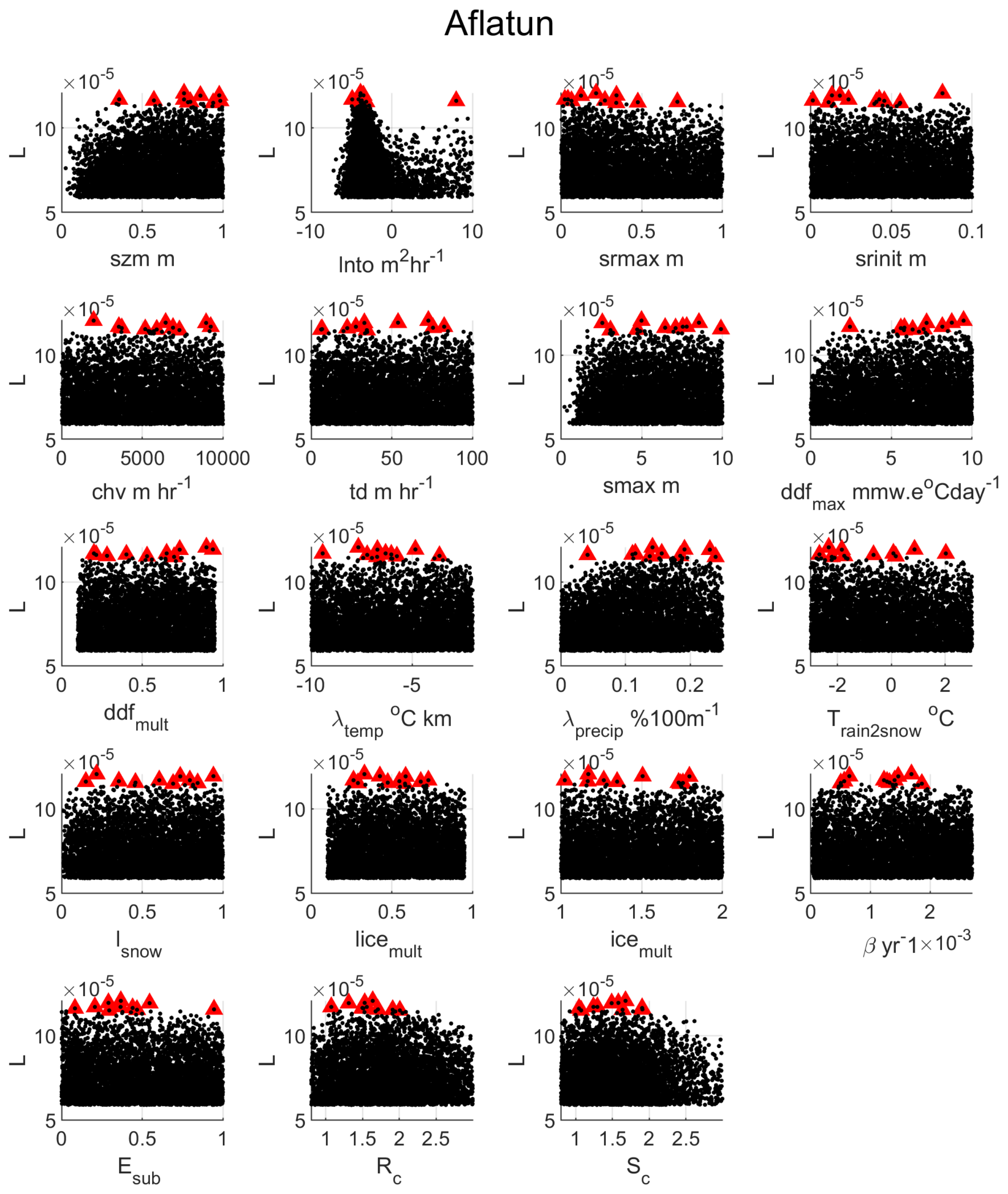

Figure S14. Dotty plots showing conditional probability values for the Aflatun catchment. The black dots show the conditional probability for the best 5000 parameters and red triangles show the conditional probability values for the best 10 simulations.

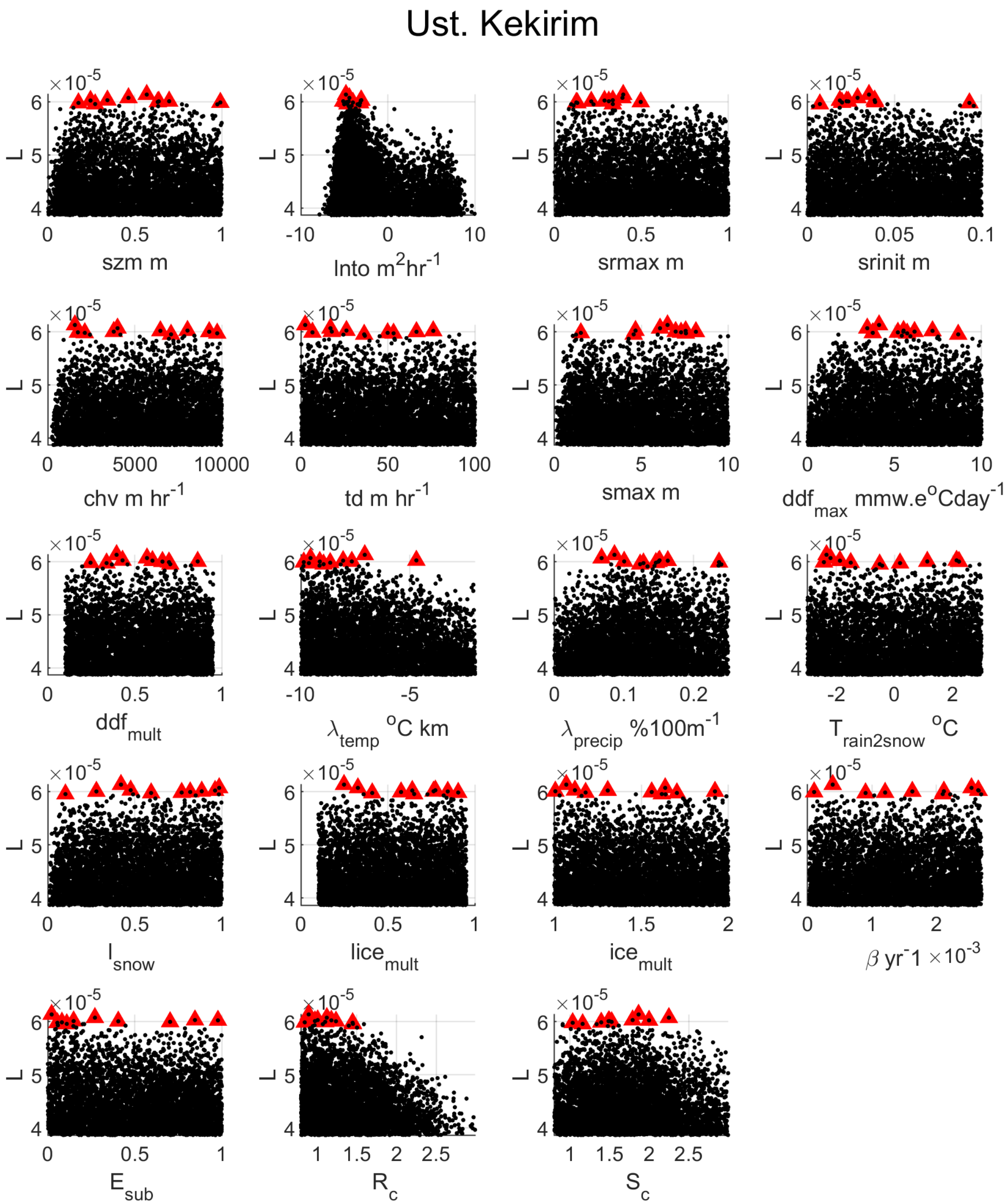

Figure S15. Dotty plots showing conditional probability values for the Ust. Kekirim catchment. The black dots show the conditional probability for the best 5000 parameters and red triangles show the conditional probability values for the best 10 simulations.

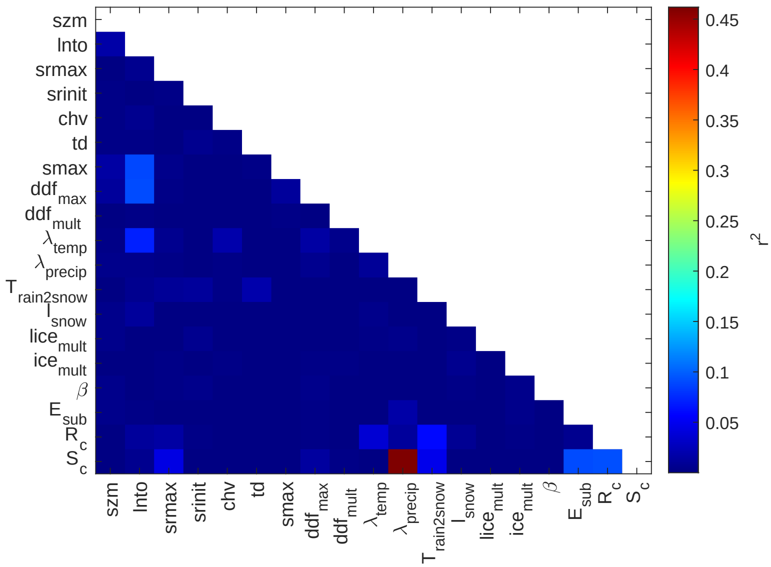

Figure S16. Coefficient of determination (r^2) between parameters pairs for the top 0.5% calibration simulations.

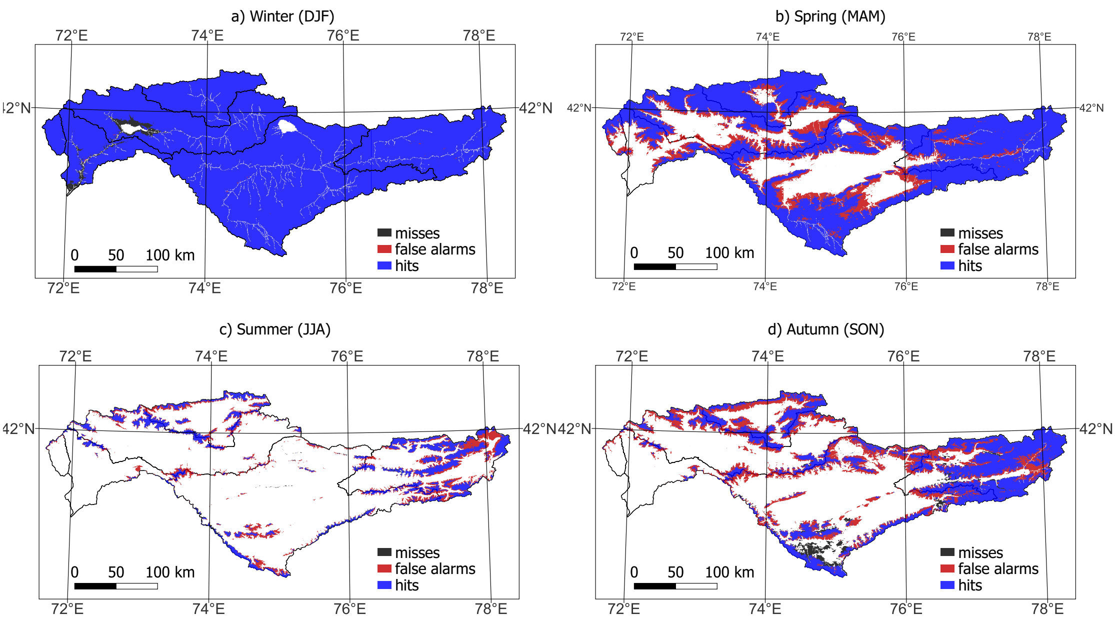

Figure S17. Spatial distribution of the hits, misses and false alarms between the simulated snow extent (5^{th} member of the 0.5% best calibration simulations) and MODIS snow extent for the year 2002. Hits, misses and false alarms are defined in Table 6.

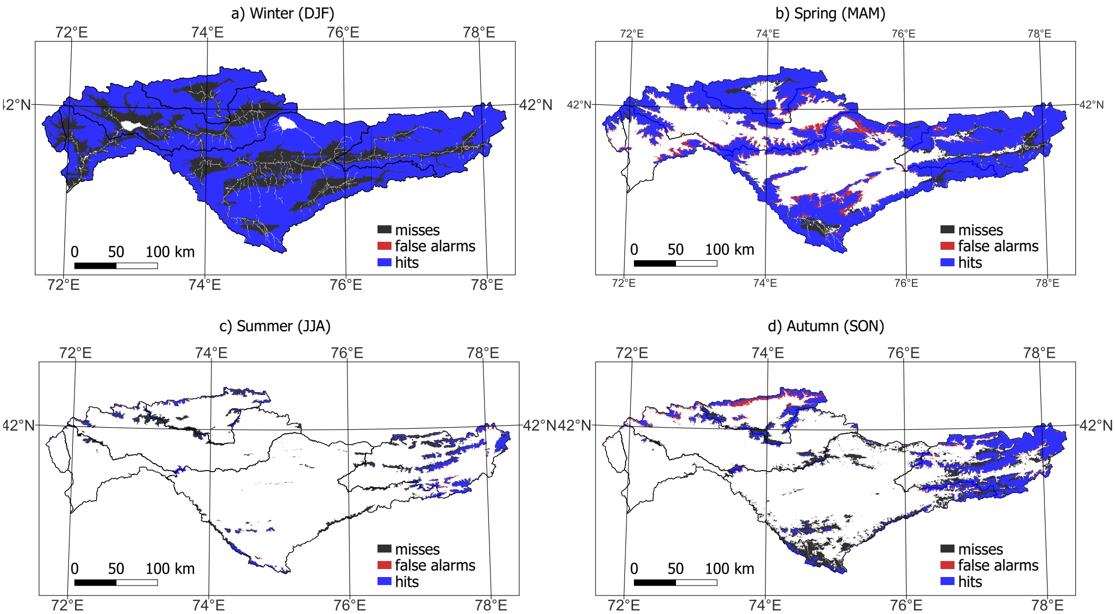

Figure S18. Spatial distribution of the hits, misses and false alarms between the simulated snow extent (95^{th} member of the 0.5% best calibration simulations) and MODIS snow extent for the year 2002.

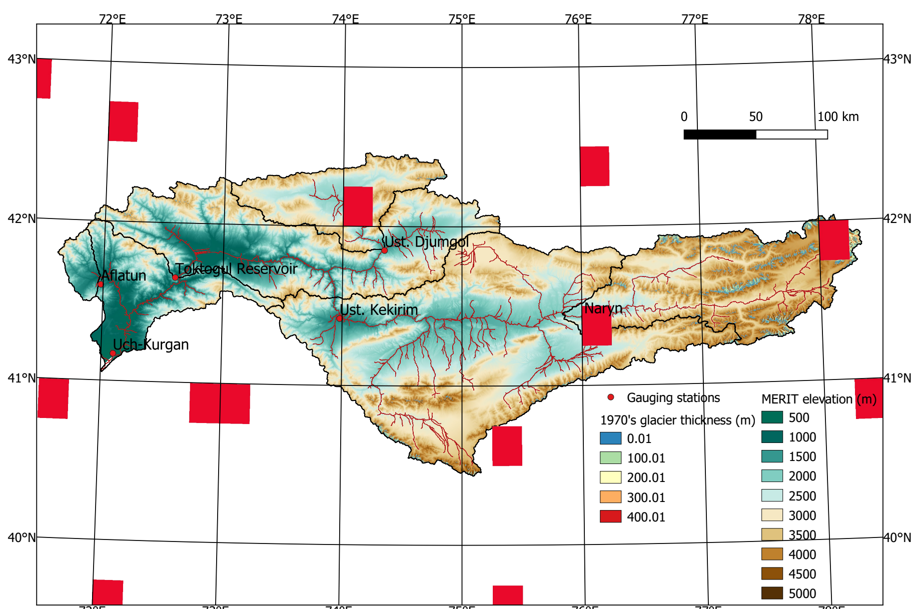

Figure S19. Red boxes show the locations of the rain gauges in January 2007 which are used to derived the APHRODITE gridded precipitation.

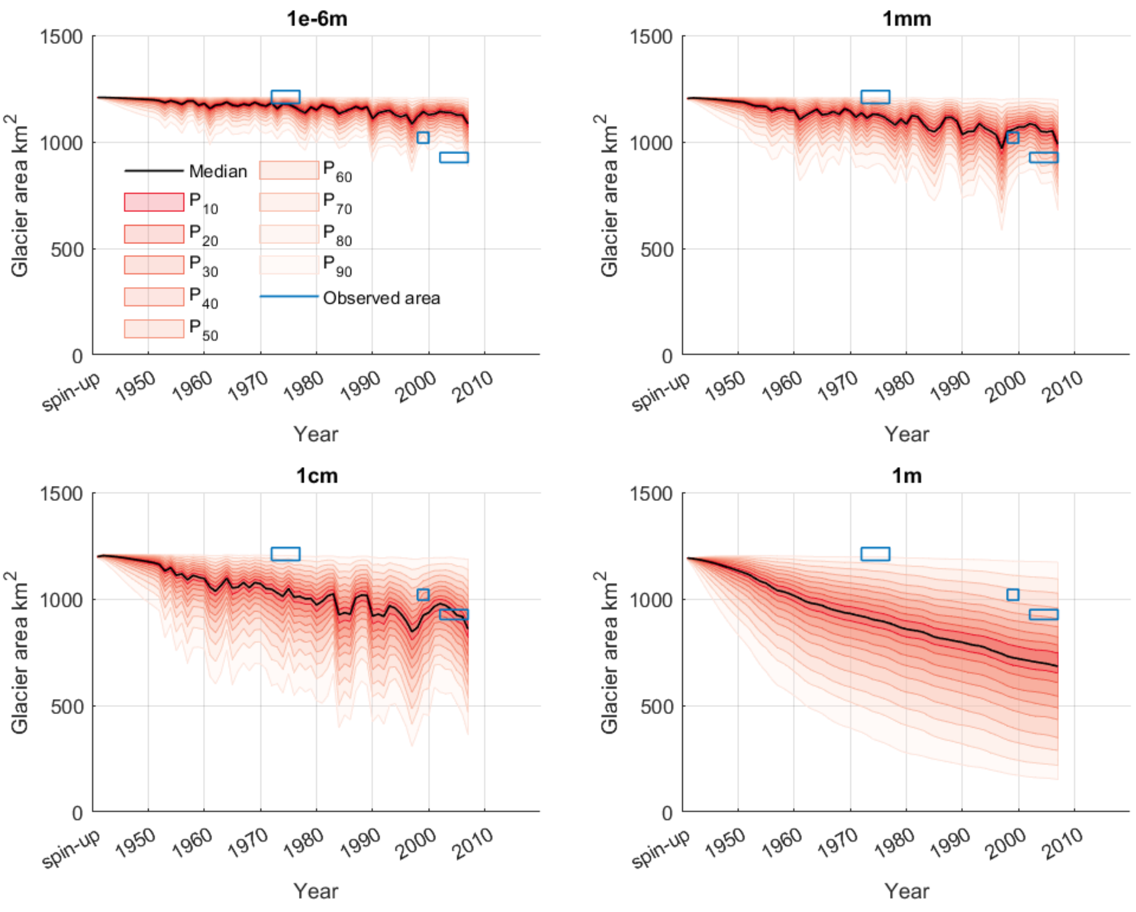

Figure S20. Catchment wide glaciated area when different ice depth thresholds are used to identify the presence of ice.

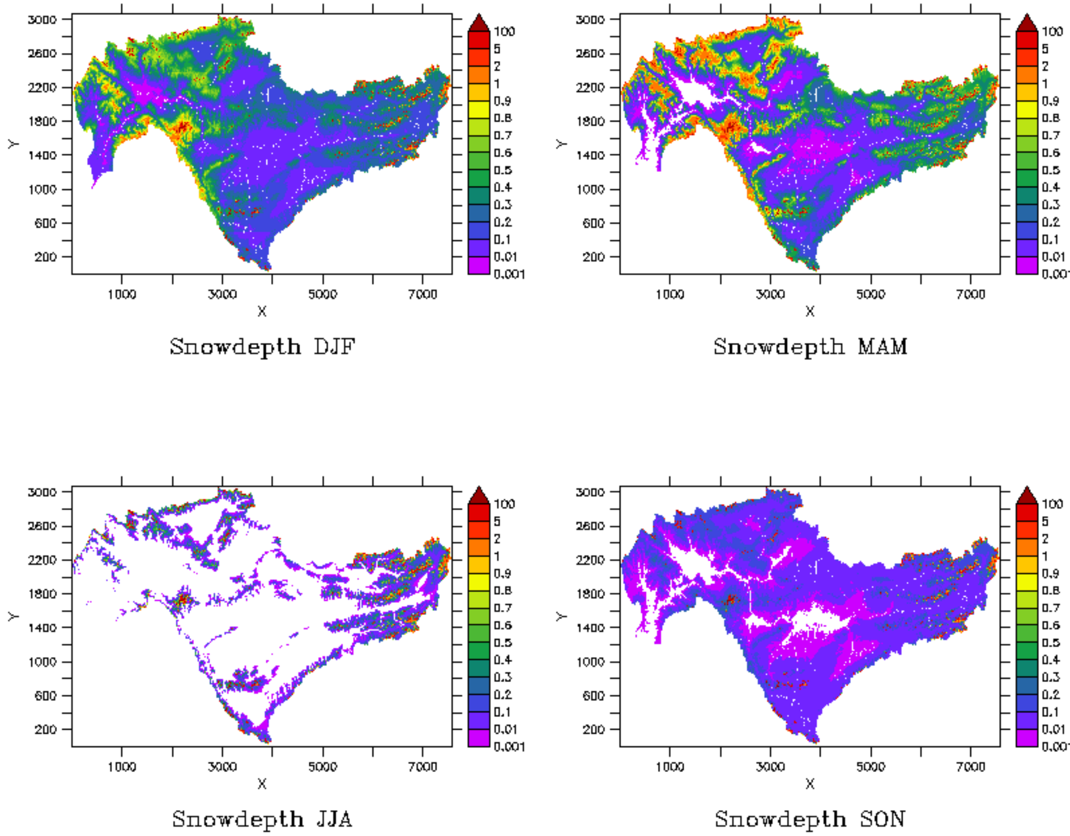

Figure S21. Simulated seasonal snow depth (m) averaged for the years 2001-2007 using output from the median (50^{th} percentile calibration simulation).

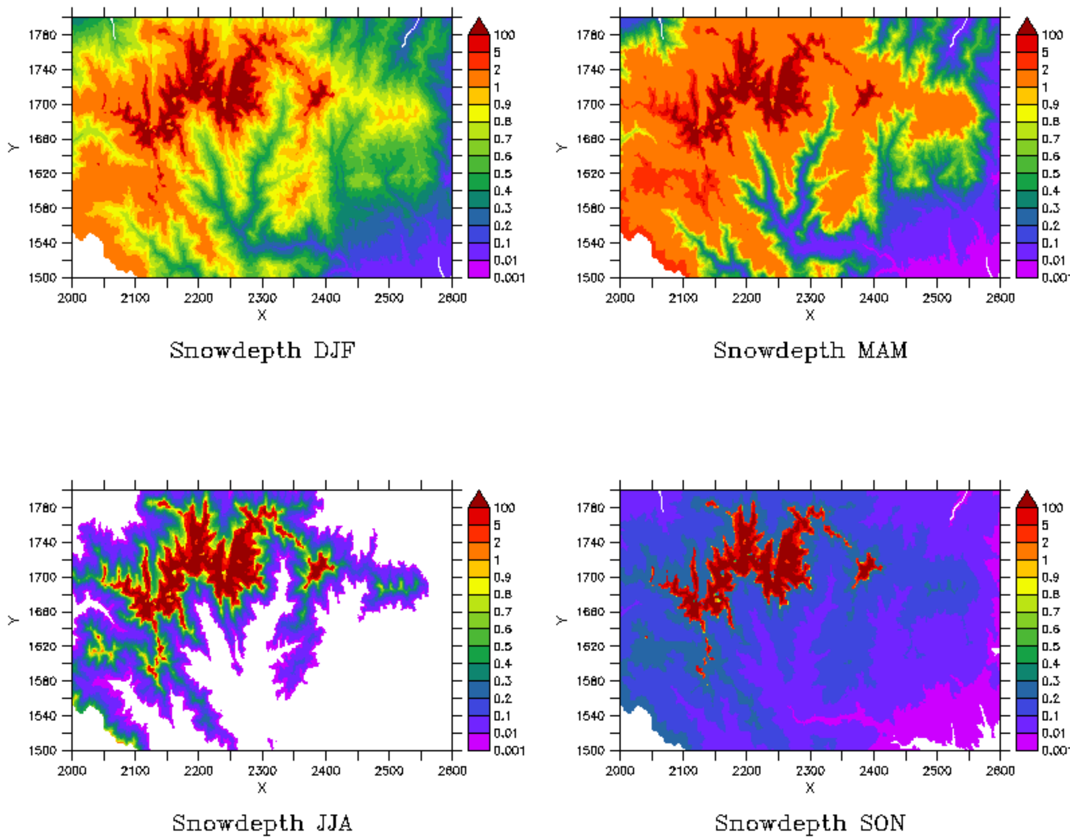

Figure S22. A zoomed in version of Fig. S21 showing the existence of a 'snow tower' in the western part of the catchment.

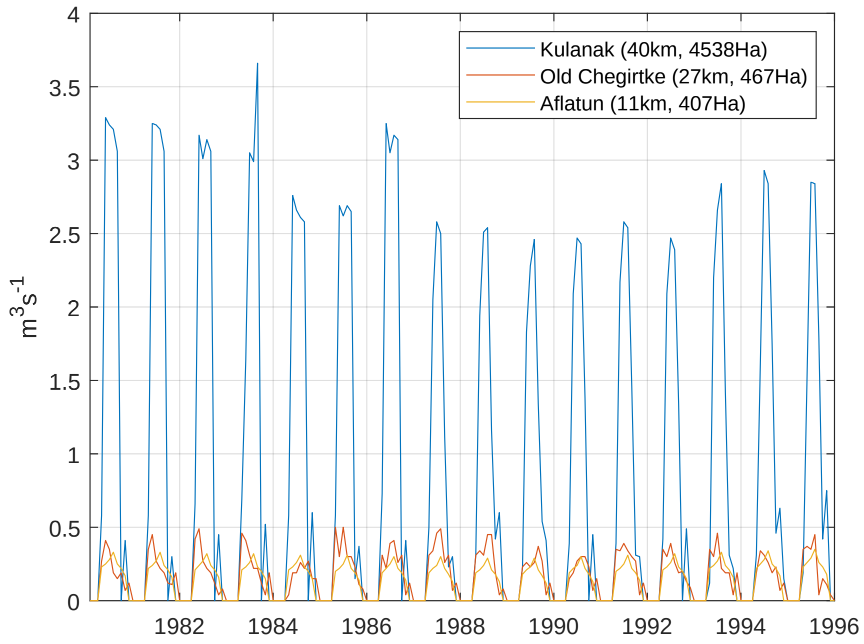

Figure S23. Monthly flow intake at irrigation channels in the Naryn catchment from the Central Asian Waterinfo Database. Length of the channel and the irrigated area is shown in the legend.

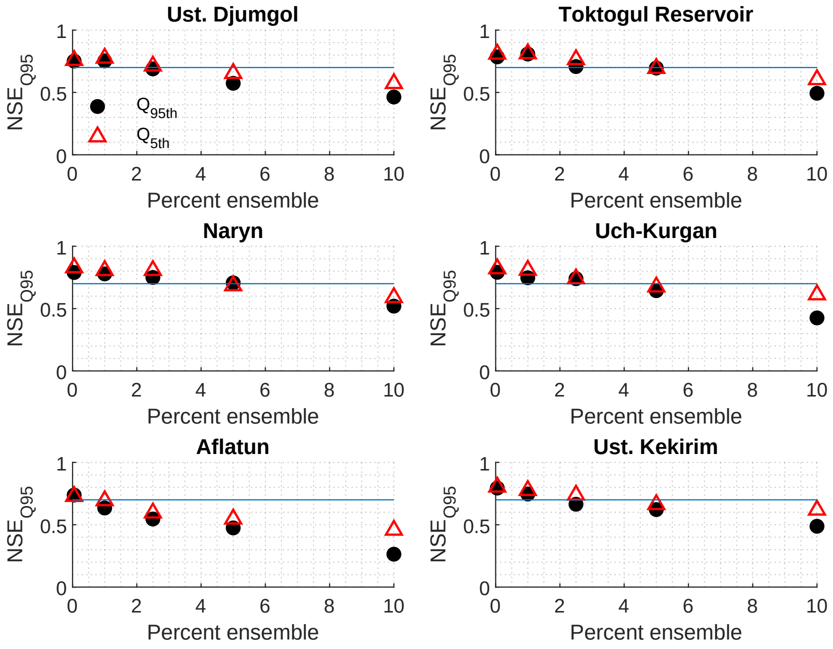

Figure S24. NSE values for the $5^{th} - 95^{th}$ percentile limits when different thresholds are used to define the behavioural simulations. Thresholds of 0.5%,1%,2.5%,5% and 10% are shown. The blue line indicates NSE values of 0.7.

Table S1. Calibration and validation performance metrics for the best 0.5% of ensemble (n=751 simulations) when homogeneous parameters are selected for the entire catchment. The table lists the metrics for the best experiment and the 5^{th} and 95^{th} percentile of conditional probability-weighted simulated discharge of the .

Station	NSE				$PBIAS$			RSR_{MAM}			RSR_{JJA}			RSR_{SON}			RSR_{DJF}		
	Best NSE	5^{th}	50^{th}	95^{th}	5^{th}	50^{th}	95^{th}	5^{th}	50^{th}	95^{th}	5^{th}	50^{th}	95^{th}	5^{th}	50^{th}	95^{th}	5^{th}	50^{th}	95^{th}
Calibration																			
Djumgol	0.84	0.78	0.66	0.76	8.42	-12.91	17.90	0.63	0.58	0.43	0.67	1.00	0.68	0.16	0.19	0.45	0.12	0.06	0.35
Toktogul	0.89	0.81	0.72	0.73	9.74	-11.91	27.47	0.59	0.39	0.55	0.55	0.96	0.52	0.21	0.17	0.53	0.24	0.12	0.50
Naryn	0.59	0.47	0.48	0.32	-35.93	-41.13	-36.99	0.46	0.62	0.48	1.33	1.27	1.54	0.33	0.30	0.27	0.12	0.05	0.17
Uch-Kurgan	0.82	0.77	0.80	0.49	25.96	2.28	50.83	0.70	0.50	0.79	0.49	0.70	0.65	0.32	0.18	0.76	0.32	0.19	0.63
Aflatun	0.74	0.66	0.45	0.66	-17.21	-33.13	-11.17	0.81	0.90	0.96	0.77	1.07	0.58	0.25	0.41	0.25	0.20	0.25	0.17
Ust. Kekirim	0.86	0.76	0.65	0.74	-2.07	-20.01	11.49	0.51	0.31	0.44	0.78	1.12	0.72	0.22	0.24	0.39	0.20	0.09	0.42
Validation																			
Djumgol	0.87	0.86	0.75	0.79	8.03	-11.85	19.75	0.44	0.43	0.42	0.57	0.89	0.57	0.10	0.16	0.42	0.12	0.06	0.37
Toktogul	0.93	0.88	0.78	0.75	11.79	-13.35	27.67	0.48	0.28	0.54	0.39	0.90	0.45	0.20	0.14	0.53	0.24	0.07	0.49
Naryn	0.58	0.45	0.50	0.16	-32.04	-41.94	-42.08	0.44	0.57	0.44	1.38	1.25	1.74	0.27	0.29	0.27	0.16	0.06	0.17
Uch-Kurgan	-0.33	-0.53	0.06	-1.10	51.33	18.38	76.93	1.34	1.17	1.56	1.87	1.42	1.94	0.75	0.47	1.26	0.42	0.30	0.74
Aflatun	0.63	0.33	0.04	0.63	-31.80	-40.83	-16.54	1.08	1.16	0.94	1.05	1.37	0.70	0.48	0.63	0.24	0.41	0.46	0.24
Ust. Kekirim	0.88	0.82	0.61	0.71	-3.35	-25.19	4.15	0.29	0.23	0.37	0.76	1.19	0.90	0.18	0.27	0.29	0.19	0.10	0.36

Station	λ_{precip} range % 100 m^{-1}	E_{sub} range
Ust. Djumgol	6 - 19	0.009 - 0.7
Toktogul Reservoir	4 - 18	0.05 - 0.6
Naryn	6 - 24	0.04 - 0.7
Uch-Kurgan	6 - 16	0.0004 – 0.8
Aflatun	4 - 24	0.08 - 0.9
Ust. Kekirim	7 - 24	0.02 - 1.0

Table S2. Parameter ranges for the best 10 performing simulations for each sub-catchment. The values are the ranges of the red markers shown in the dotty plots Figs. S10-S15. Values ranges for the precipitation lapse rates (λ_{precip}) and the snow and ice sublimation factor E_{sub} are listed.

Table S3. Initial and calibrated parameter ranges for each sub-catchment for the best 0.5% of ensemble (n=751 simulations). . Parameter values for the best simulation are listed.

Parameter	Initial range	Ust Djumgol Best	Ust Djumgol Min	Ust Djumgol Max	Toktogul Reservoir Best	Toktogul Reservoir Min	Toktogul Reservoir Max	Naryn Best	Naryn Min	Naryn Max	Uch-Kurgan Best	Uch-Kurgan Min	Uch-Kurgan Max	Alfatun Best	Alfatun Min	Alfatun Max	Ust Kekirim Best	Ust Kekirim Min	Ust Kekirim Max
SZM	0.001 1	0.568	0.087	1.000	0.299	0.010	0.999	0.162	0.004	1.000	0.295	0.025	1.000	0.759	0.091	1.000	0.568	0.037	0.999
$ln(T0)$	-20 20	-4.837	-6.662	7.960	-4.270	-6.948	8.476	-4.701	-8.109	6.225	-4.795	-6.954	9.028	-3.904	-5.563	9.860	-4.837	-6.948	7.342
SR_{max}	0.001 1	0.396	0.005	0.999	0.234	0.005	0.999	0.405	0.003	1.000	0.566	0.009	0.996	0.217	0.003	0.999	0.396	0.005	0.999
SR_{init}	0.00 0.10	0.04	0.00	0.10	0.03	0.00	0.10	0.06	0.00	0.10	0.02	0.00	0.10	0.08	0.00	0.10	0.04	0.00	0.10
CHV	1 10000	1557	283	9990	7508	411	9993	5858	552	10000	6712	367	9990	1983	16	9999	1557	609	9997
T_d	0.1 100.0	2.4	0.1	99.9	79.9	0.1	99.9	35.7	0.3	99.9	2.3	0.1	99.8	72.5	0.3	99.9	2.4	0.1	99.8
S_{max}	0.1 10.0	6.5	0.1	10.0	4.2	0.4	10.0	3.6	0.2	10.0	6.9	0.2	10.0	5.0	0.9	10.0	6.5	0.5	10.0
ddf_{max}	0.0 10.0	4.1	0.3	10.0	5.7	0.3	10.0	6.3	0.4	10.0	4.5	0.3	10.0	9.5	0.3	10.0	4.1	0.3	10.0
ddf_{mult}	0.1 0.95	0.40	0.10	0.95	0.21	0.10	0.95	0.92	0.10	0.95	0.45	0.10	0.95	0.90	0.10	0.95	0.40	0.10	0.95
λ_{temp}	-10.0 -2.0	-7.1	-10.0	-2.0	-8.5	-10.0	-2.1	-2.1	-10.0	-2.0	-8.1	-10.0	-2.0	-7.7	-10.0	-2.0	-7.1	-10.0	-2.1
λ_{precip}	0.0 25.0	8.6	0.0	25.0	14.7	0.0	24.8	18.8	0.0	24.9	8.4	0.0	24.8	14.2	0.1	25.0	8.6	0.1	25.0
T_c	-3.0 3.0	-2.3	-3.0	3.0	-1.6	-3.0	3.0	-2.7	-3.0	3.0	-2.4	-3.0	3.0	-2.3	-3.0	3.0	-2.3	-3.0	3.0
l_{snow}	0.0 1.0	0.4	0.0	1.0	0.8	0.0	1.0	0.8	0.1	1.0	0.5	0.0	1.0	0.2	0.0	1.0	0.4	0.0	1.0
$l_{ice_{mult}}$	0.1 0.95	0.25	0.10	0.95	0.42	0.10	0.95	0.39	0.10	0.95	0.32	0.10	0.95	0.33	0.10	0.95	0.25	0.10	0.95
ice_{mult}	1.0 2.0	1.1	1.0	2.0	1.4	1.0	2.0	1.1	1.0	2.0	1.7	1.0	2.0	1.2	1.0	2.0	1.1	1.0	2.0
β	2.74E-05 2.74E-03	3.91E-04	3.20E-05	2.70E-03	1.94E-03	3.20E-05	2.70E-03	1.96E-03	2.80E-05	2.70E-03	3.99E-04	3.20E-05	2.70E-03	1.69E-03	2.80E-05	2.70E-03	3.91E-04	3.20E-05	2.69E-03
E_{sub}	0.0 1.0	0.0	0.0	1.0	0.2	0.0	1.0	0.2	0.0	1.0	0.7	0.0	1.0	0.4	0.0	1.0	0.0	0.0	1.0
R_c	0.8 3.0	0.9	0.8	3.0	1.2	0.8	2.5	1.0	0.8	3.0	1.2	0.8	2.3	1.6	0.8	3.0	0.9	0.8	2.3
S_c	0.8 3.0	1.9	0.8	3.0	1.3	0.8	3.0	2.0	0.8	3.0	2.0	0.8	2.9	1.7	0.8	3.0	1.9	0.8	3.0

Table S4. Validation metrics between seasonal simulated (50^{th} median member) and observed MODIS snow extent for individual years. Seasonal snow extent is calculated from weekly snow extent.

	Year	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)
Error bias (E)	2001	1.23	4.98	37.72	15.36
	2002	0.04	18.24	4.14	14.80
	2003	0.10	0.80	5.60	104.17
	2004	0.34	4.24	7.01	8.81
	2005	0.14	2.59	3.82	30.67
	2006	0.37	2.46	1.64	55.51
	2007	5.58	7.60	13.67	5.41
	Mean	1.11	5.84	10.51	33.53
Hit rate (H)	2001	0.99	0.97	0.96	0.97
	2002	0.99	0.99	0.86	0.94
	2003	0.97	0.93	0.88	0.99
	2004	0.97	0.97	0.88	0.93
	2005	0.97	0.96	0.82	0.97
	2006	0.95	0.95	0.73	0.99
	2007	0.96	0.95	0.90	0.84
	Mean	0.97	0.96	0.86	0.95
Critical success index (C)	2001	0.97	0.85	0.37	0.70
	2002	0.99	0.82	0.55	0.49
	2003	0.97	0.88	0.53	0.59
	2004	0.97	0.85	0.47	0.57
	2005	0.97	0.88	0.48	0.54
	2006	0.94	0.85	0.50	0.57
	2007	0.80	0.68	0.39	0.46
	Mean	0.94	0.83	0.47	0.56
False alarms (F)	2001	0.01	0.13	0.62	0.29
	2002	0.00	0.17	0.40	0.49
	2003	0.00	0.06	0.43	0.41
	2004	0.01	0.13	0.49	0.40
	2005	0.00	0.09	0.46	0.45
	2006	0.02	0.11	0.38	0.42
	2007	0.17	0.29	0.60	0.50
	Mean	0.03	0.14	0.48	0.42

Table S5. Monthly climatological discharge components for the $5^{th} - 95^{th}$ percentile limits (%) for the top 0.5% calibration simulations. Climatologies are calculated by averaging monthly data over the period 1951-2007. Values refer to the ranges shown in Fig. 12. The glacier melt contribution to discharge is shown in red.

Station	Component	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Djumgol	Snow melt	39 - 95	37 - 94	37 - 94	44 - 96	62 - 98	70 - 99	66 - 99	58 - 97	53 - 97	47 - 97	44 - 96	41 - 96
	Glacier melt	0 - 1	0 - 1	0 - 1	0 - 1	0 - 0	0 - 1	0 - 3	0 - 6	0 - 3	0 - 2	0 - 1	0 - 1
	Rainfall	5 - 61	6 - 63	6 - 63	3 - 56	1 - 38	1 - 30	0 - 33	1 - 39	2 - 46	3 - 53	4 - 56	4 - 59
Toktogul Reservoir	Snow melt	38 - 90	36 - 89	36 - 89	48 - 93	62 - 97	66 - 98	59 - 95	46 - 91	45 - 91	44 - 92	41 - 92	39 - 91
	Glacier melt	0 - 9	0 - 9	0 - 8	0 - 5	0 - 2	0 - 2	0 - 11	2 - 25	1 - 16	0 - 12	0 - 10	0 - 10
	Rainfall	8 - 61	9 - 63	9 - 63	6 - 51	3 - 38	2 - 34	1 - 35	0 - 37	2 - 46	4 - 55	5 - 57	6 - 60
Naryn	Snow melt	33 - 84	32 - 83	31 - 82	31 - 82	35 - 86	41 - 92	28 - 84	18 - 77	28 - 81	35 - 85	35 - 85	34 - 84
	Glacier melt	0 - 29	0 - 27	0 - 25	0 - 24	0 - 22	0 - 22	**3-53**	**10-66**	**5-46**	0 - 38	0 - 34	0 - 31
	Rainfall	9 - 64	11 - 65	13 - 66	14 - 67	11 - 61	3 - 50	-2 - 43	-6 - 37	-5 - 51	-1 - 61	4 - 62	7 - 64
Uch-Kurgan	Snow melt	38 - 91	37 - 90	37 - 90	52 - 94	64 - 97	67 - 98	61 - 95	49 - 91	46 - 91	44 - 92	41 - 92	40 - 92
	Glacier melt	0 - 8	0 - 8	0 - 7	0 - 4	0 - 1	0 - 1	0 - 10	2 - 23	1 - 15	0 - 11	0 - 10	0 - 9
	Rainfall	7 - 61	8 - 63	8 - 61	5 - 47	2 - 35	1 - 32	1 - 34	0 - 38	2 - 46	4 - 54	5 - 57	6 - 59
Aflatun	Snow melt	52 - 97	51 - 96	52 - 97	67 - 99	75 - 99	79 - 100	76 - 99	72 - 99	64 - 98	59 - 98	56 - 98	54 - 97
	Glacier melt	0 - 0	0 - 0	0 - 0	0 - 0	0 - 0	0 - 0	0 - 0	0 - 0	0 - 0	0 - 0	0 - 0	0 - 0
	Rainfall	3 - 48	4 - 49	3 - 48	1 - 33	1 - 25	0 - 21	1 - 24	1 - 28	2 - 36	2 - 41	2 - 44	3 - 46
Ust. Kekirim	Snow melt	36 - 87	35 - 86	35 - 86	48 - 91	61 - 96	62 - 96	49 - 92	36 - 86	40 - 87	41 - 89	39 - 89	38 - 88
	Glacier melt	0 - 16	0 - 15	0 - 13	0 - 9	0 - 3	0 - 4	1 - 24	3 - 41	2 - 26	0 - 21	0 - 18	0 - 17
	Rainfall	9 - 62	10 - 63	11 - 63	8 - 51	4 - 39	2 - 37	0 - 38	1 - 38	0 - 47	4 - 57	6 - 59	8 - 61