Supplementary Information for "Swiss glacier mass loss during the 2022 drought: persistent streamflow contributions amid declining melt water volumes"

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Supplementary Tables and Figures

Table S1 Overview of the 88 catchments used in the study. Area refers to catchment area. The column "Fig. 3" indicates the catchment that were used in Figure 3, in which the water balance anomalies were calculated, column "Fig. 4" refers to catchments used for calculating a compensation level, column "Fig 5." to catchments used for calculating glacier melt contribution to streamflow, column "Fig 6." to catchments used in the long-term comparison (time-series starting before 1921) and column "Fig 7." to catchments used for comparing streamflow in the year 2003 and 2022, and SI Fig. 4, for Figure 4 of the SI.

Catchment	Area [km^2]	Glacier cover	Basin	Fig. 3	Fig. 4	Fig. 5	Fig. 6	Fig. 7	SI Fig. 4
Martina_2067	1941.29	2.5	Inn	x	x	x	x	x	x
St-Moritzbad_2105	155.39	3.7	Inn			x	x	x	
Pontresina_2256	66.53	22.3	Inn	x	x	x		x	
Pontresina_2262	106.92	15.1	Inn	x	x	x		x	x
La-Punt-Chamues_2263	73.36	0.0	Inn	x	x	x		x	
Tarasp_2265	1580.76	3.0	Inn					x	
S-Chanf_2462	615.94	6.3	Inn			x		x	
Bellinzona_2020	1517.49	0.2	Po	x	x	x	x	x	x
Loderio_2086	400.23	0.3	Po				x	x	
Piotta_2364	158.88	0.4	Po					x	
Maggia_2368	926.95	0.3	Po					x	
Buseno_2474	120.53	0.2	Po	x	x	x		x	
Bignasco_2475	315.51	0.8	Po					x	
Pollegio_2494	443.76	0.2	Po	x	x	x		x	
Soglio_2620	177.36	7.1	Po						x
Brugg_2016	11681.18	1.5	Rhine	x	x	x	x	x	
Brienzwiler_2019	555.15	15.3	Rhine	x	x	x	x	x	
Brügg-Aegerten_2029	8248.58	2.1	Rhine	x	x	x	x	x	
Thun_2030	2459.26	6.9	Rhine	x	x	x	x		
Ilanz_2033	774.04	2.0	Rhine	x	x	x	x	x	
Seedorf_2056	833.20	6.7	Rhine	x	x	x	x	x	
Murgenthal_2063	10059.27	1.7	Rhine	x	x	x		x	
Hagneck_2085	5111.84	3.4	Rhine	x	x	x		x	
Andermatt_2087	190.18	3.2	Rhine	x	x	x	x	x	
Luetschine_2109	380.66	13.4	Rhine	x	x	x	x	x	x
Bern_2135	2941.14	5.8	Rhine	x	x	x	x	x	
Tiefencastel_2141	529.04	0.5	Rhine			x	x	x	
Rekingen_2143	14767.35	0.2	Rhine	x	x	x		x	
Landquart_2150	613.74	0.8	Rhine			x		x	
Oberwil_2151	343.70	2.5	Rhine	x	x	x		x	
Broc_2160	636.30	0.3	Rhine	x	x	x		x	

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Catchment	Area [km^2]	Glacier cover	Basin	Fig. 3	Fig. 4	Fig. 5	Fig. 6	Fig. 7	SI Fig. 4
Weisse_Luetschine_2200	164.92	13.0	Rhine	x	x	x		x	x
Untersiggenthal_2205	17553.22	1.5	Rhine	x	x	x	x	x	
Oberried_Lenk_2219	34.75	23.4	Rhine	x	x	x		x	
Isenthal_2276	43.87	7.1	Rhine	x	x	x		x	
Neuhausen_2288	11929.59	0.3	Rhine	x	x	x	x	x	
Basel-Rheinhalle_2289	35877.83	0.8	Rhine	x	x	x	x	x	x
Davos_2355	183.68	0.3	Rhine	x	x	x		x	
Mollis_2372	600.21	3.0	Rhine	x	x	x	x	x	
Fürstenau_2387	1576.85	0.6	Rhine	x	x	x		x	
Seez_2426	106.07	0.1	Rhine					x	
Rein_da_Sumvitg_2430	21.76	1.5	Rhine	x	x	x		x	
Ringgenberg_2457	1137.55	12.0	Rhine	x	x	x		x	
Diepoldsau_2473	6299.20	0.6	Rhine	x	x	x	x	x	
Buochs_2481	227.96	2.7	Rhine	x	x	x	x	x	
Glenner_2498	380.88	1.0	Rhine	x	x	x		x	
Domat-Ems_2602	3228.55	0.9	Rhine	x	x	x	x	x	
Hinterrhein_2631	41.52	9.4	Rhine			x			
Linth_47160303	195.61	7.6	Rhine			x			
Louibach_A011	62.65	3.2	Rhine	x	x	x		x	
Aareschlucht_A095	453.76	17.1	Rhine	x	x	x			
Kander_A096	141.71	15.9	Rhine	x	x	x			
Grindelwald_A112	106.74	27.8	Rhine			x			
PorteduScex_2009	5238.08	11.1	Rhone	x	x	x	x	x	x
Sion_2011	3372.39	14.4	Rhone	x	x	x	x	x	
Branson_2024	3727.84	13.2	Rhone	x	x	x		x	
Martigny_2053	675.65	11.6	Rhone					x	
Drance_de_Bagnes_2117	253.72	22.1	Rhone					x	
Blatten bei Naters_2160	195.52	56.4	Rhone	x	x	x		x	
Aigle_2203	131.59	0.9	Rhone	x	x	x		x	
Klusmatten_2244	19.44	0.4	Rhone	x	x	x		x	
Gletsch_2268	39.41	42.8	Rhone	x	x	x		x	x
Blatten_2269	77.37	24.3	Rhone	x	x	x		x	
Brig_2342	76.52	2.5	Rhone	x	x	x		x	
Brig_2346	906.06	19.4	Rhone	x	x	x		x	

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Catchment	Area [km^2]	Glacier cover	Basin	Fig. 3	Fig. 4	Fig. 5	Fig. 6	Fig. 7	SI Fig. 4
Visp_2351	785.83	23.6	Rhone					x	
Reckingen_2419	214.25	12.0	Rhone	x	x	x		x	
Geneve_2606	8000.36	7.3	Rhone	x	x	x	x	x	
Oberwald_2607	38.59	4.4	Rhone	x	x	x		x	
Gornera	80.50	64.8	Rhone	x	x	x		x	
Zmuttbach	40.81	47.1	Rhone	x	x	x		x	
Findelbach	22.02	70.0	Rhone	x	x	x		x	
LaBorgne_deFerpecle	34.33	57.5	Rhone	x	x	x		x	
LaBorgne_d'Arolla	25.20	39.8	Rhone			x		x	
Reuse_de_Saleinaz	19.90	44.1	Rhone			x		x	
Moiry	28.90	17.3	Rhone			x			
Turtmänna	28.00	43.3	Rhone			x			
LaNavisence	76.60	30.1	Rhone			x			
L'Avancon	78.20	1.7	Rhone			x			
Griessee	10.04	45.2	Rhone	x	x	x		x	
Saaser_Vispa	99.54	24.5	Rhone	x	x	x		x	
Mauvoisin	114.46	32.4	Rhone	x	x	x		x	
Torrent_deCorbassiere	34.63	52.6	Rhone	x	x	x		x	
Schweibbach	9.55	18.9	Rhone	x	x	x			
Furggbach	9.06	47.7	Rhone	x	x	x		x	
Schalibach	17.22	41.7	Rhone	x	x	x		x	
Triftbach	11.83	40.7	Rhone	x	x	x		x	
HautArolla	12.88	32.3	Rhone	x	x	x		x	

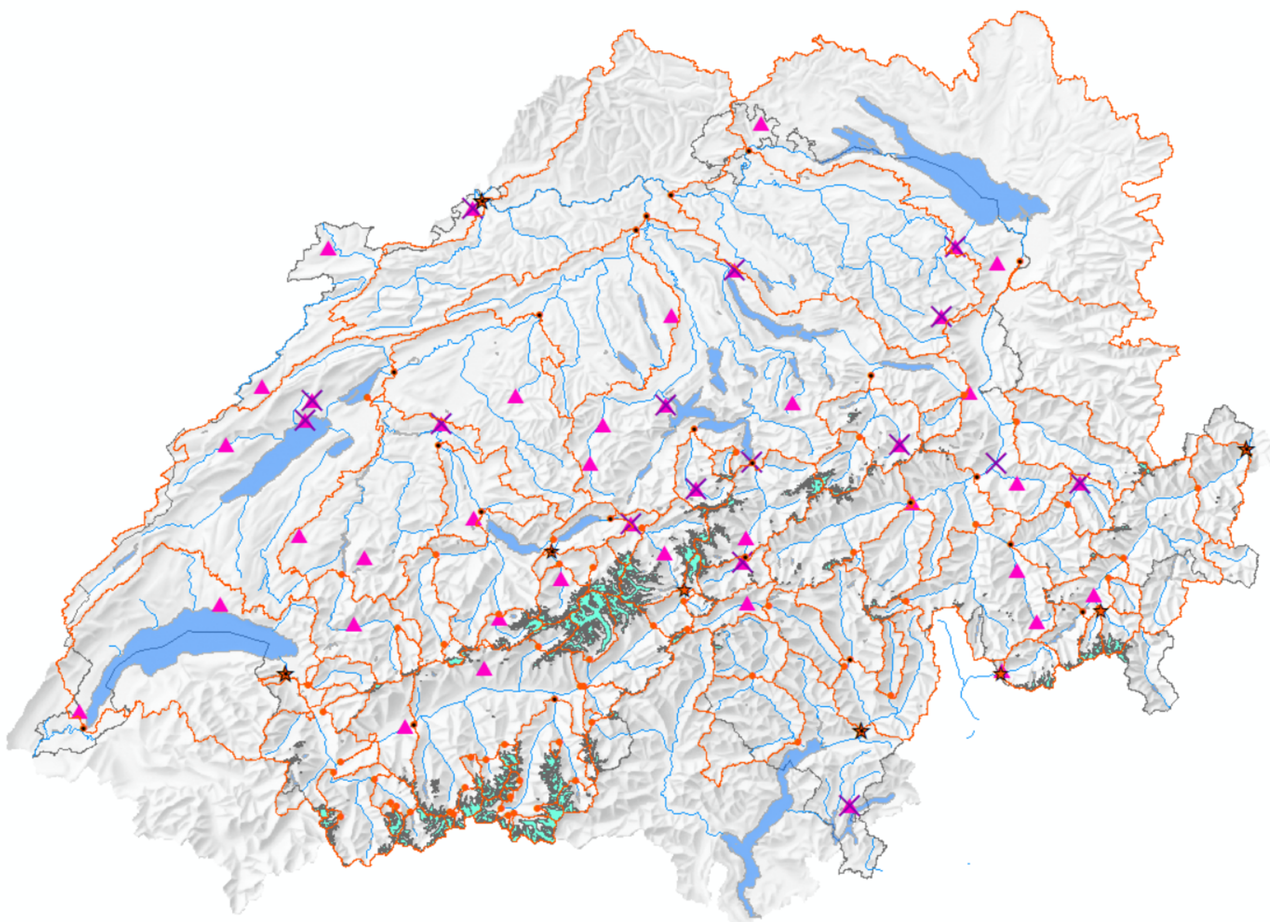

Figure S1: Location of the meteorological stations that were used for the long-term (1900-2022) analyses. Triangles show locations of precipitation measurements, whereas purple crosses show the locations of temperature measurements. The anomalies of these stations were averaged to obtain a Swiss-wide precipitation and temperature anomaly time-series from 1900 to 2022.

Table S2 List of glaciers that were used for extrapolating observed annual and winter mass balances in space and for modelling annual daily cumulative mass balance cycles that were consequently also extrapolated in space.

Glacier	Mass balance years
Adler	2006-2022
Vadrec da l'Albigna	1955-1961
Grosser Aletschgletscher	1915-2022
Allalingletscher	1956-2022
BlauSchnee	2007-2018
Ghiacciaio del Basodino	1992-2022
Chessjengletscher	1956-1995
Claridenfirn	1915-2022
Glacier de Corbassière	1997-2022
Vadret dal Corvatsch	2013-2022
Findelgletscher	2005-2022
Vadrec del Forno	1955-1960
Glacier du Giétro	1967-2022
Griesgletscher	1962-2022
Hohlaubgletscher	1956-2022
Limmerngletscher	1948-1985
Vadret dal Murtel	2014-2022
Vadret Pers	2002-2022
Pizolgletscher	2007-2021
Glacier de la Plaine Morte	2010-2022
Plattalva	1948-1985
Rhonegletscher	1885-1909 + 1980-1982 + 2007-2022
Schwarzwasserfirn/Schwarzbach	2013-2021
Schwarzberggletscher	1956-2022
Glacier du Sex Rouge	2012-2022
Silvrettagletscher	1915-2022
St. Annafirn	2012-2022
Glacier de Tsanfleuron	2010-2022

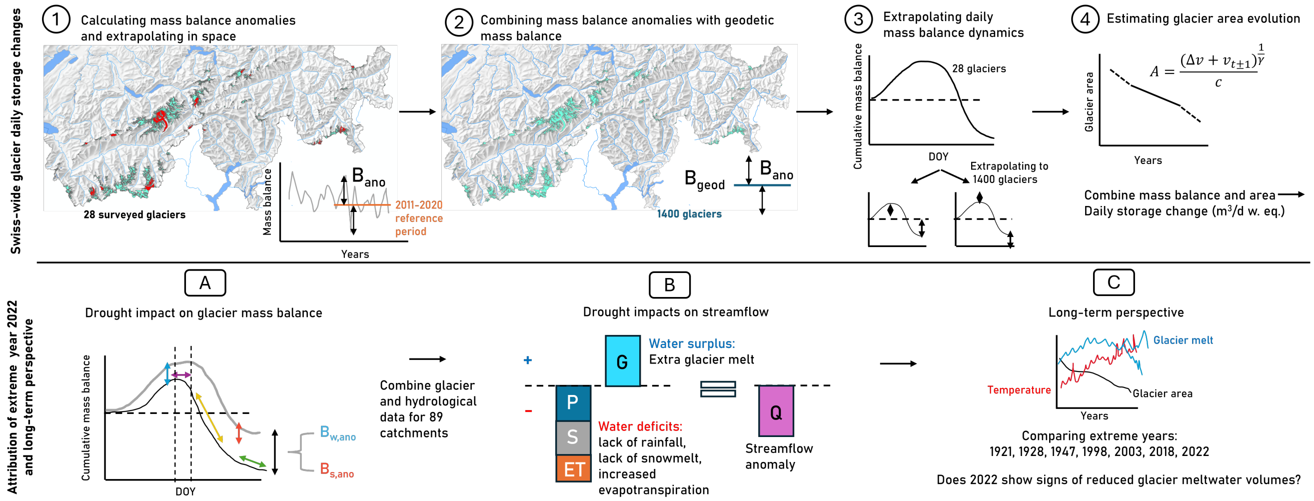

Figure S2: Schematic representation of the workflow of this study. The upper row represents the four steps that were taken to derive daily glacier storage changes for all individual Swiss glaciers from 1916 to 2022. The bottom row represents the main analyses parts in this study: A) investigating the causes of the extreme glacier melt year 2022 in terms of accumulation and ablation processes and their timing and magnitude, B) bringing together the glacier (G) and streamflow data (Q), together with precipitation (P), snowmelt (S) and evapotranspiration (ET) to analyze the drivers of streamflow deficits and surpluses, and C) Analyzing the changing glacier melt water volumes over time during extreme years.

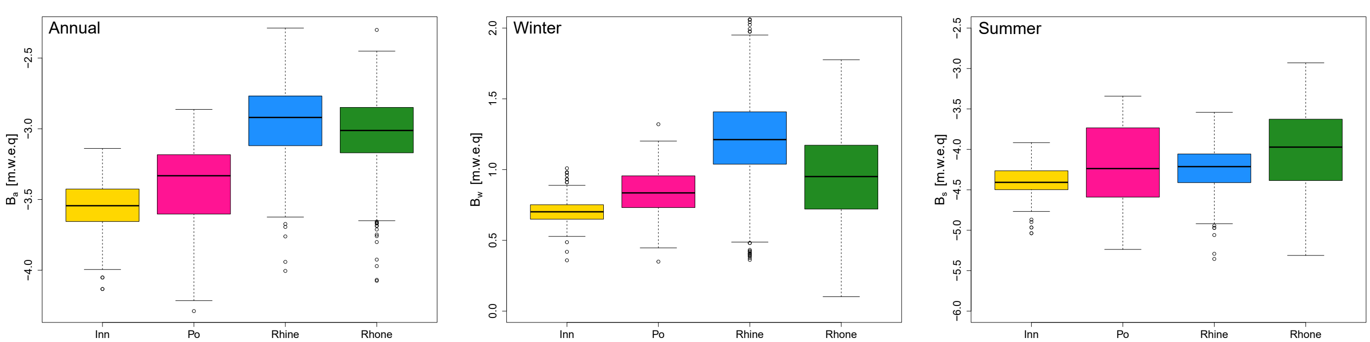

Figure S3: Distribution of glacier specific annual, winter and summer mass balances for the four main basins.

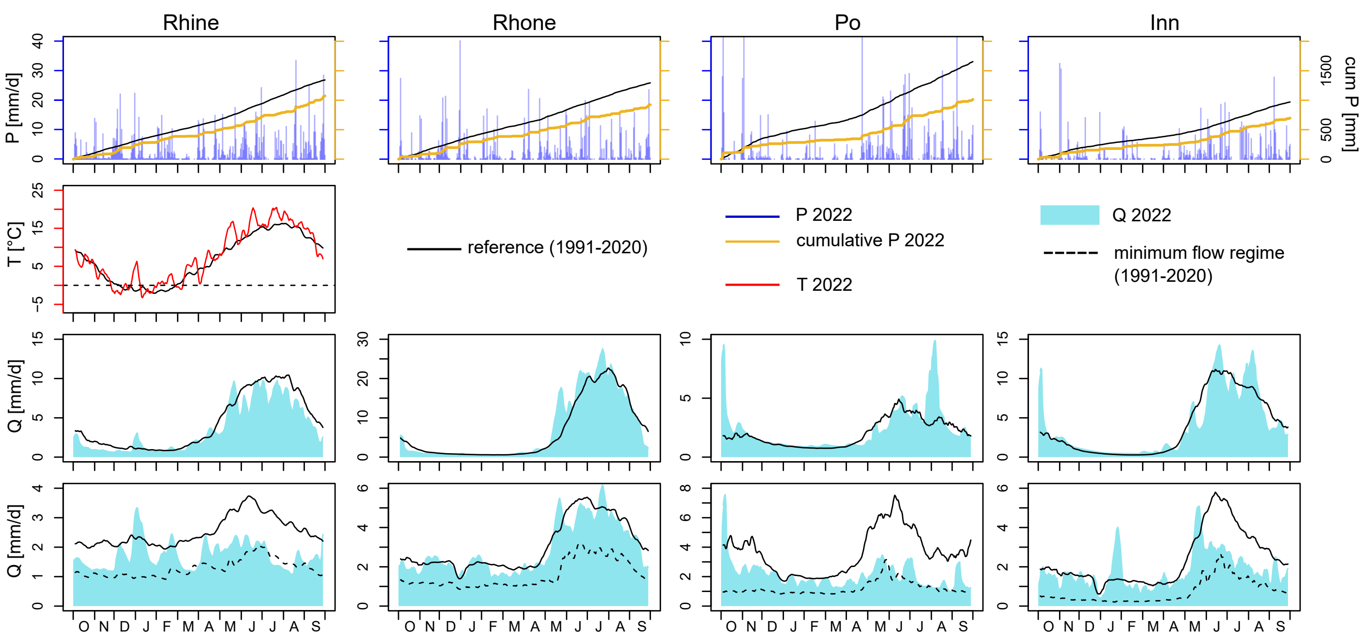

Figure S4: Precipitation (first row), temperature (second row) and the hydrological regimes of up (third row)- and downstream (fourth row) catchments in the four main river basins Rhine, Rhone, Po and Inn (columns). The selected outlets for the hydrological regime plots are indicated on Figure 1 in the main manuscript. Since the temperature anomalies over the year 2022 are very similar across the basins, only the results for the Rhine basin are shown. Variables in row 2-4 represent 7-day moving averages. The minimum flow regime corresponds to the 7-day minimum flow for each day in the period 1991-2020.

Table S3 Glacier meltwater volumes and mass balances for 2022 and the reference period (1991-2020). M refers to meltwater volumes, whereas B refers to glacier-wide mean specific mass balance. a refers to net annual, s to summer and w to winter. CH/Basin refers to Swiss-wide/Basin average or sum. Strat. refers to the stratigraphic mass balance year; used in the glacier attribution analyses, and fixed to the mass balance year corresponding to the hydrological year; used in all other comparisons and analyses.

		2022		**Reference period**	
		strat.	fixed.	strat.	fixed
M_a [km^3]	CH	2.63	2.58	0.79	0.82
	Rhine	0.76	0.73	0.25	0.26
	Rhone	1.65	1.62	0.45	0.46
	Po	0.09	0.09	0.04	0.04
	Danube	0.13	0.13	0.05	0.05
M_s [km^3]	CH	3.65	3.60	2.82	2.82
	Rhine	1.13	1.11	0.93	0.94
	Rhone	2.23	2.20	1.59	1.59
	Po	0.12	0.12	0.12	0.12
	Danube	0.17	0.17	0.17	0.17
B_a [m]	CH	-3.2	-3.1	-0.8	-0.8
B_w [m]	CH	+1.0	+1.0	1.5	+1.2
B_s [m]	CH	-4.2	-4.1	-2.3	-2.0

Hydro-meteorological conditions of 2022

In all catchments, the 2022 annual temperature anomalies were around +1°C compared to the reference period 1991-2020. For 20% of the catchments, mostly located in the southern part of Switzerland, 2022 ranks first for annual mean temperatures, based on the period 1961-2022. For all other catchments, 2022 was either the second, or third hottest year (after 2020 and 2007). The summer (JJA) of 2022 was the hottest for 18% of the catchments, whereas for the other catchments it ranked second after the summer of 2003. The summer temperature anomaly ranged between +1.8 and +2.7 °C. At a monthly scale, especially, May, June and July stood out, with monthly temperature anomalies of +3°C (Figure SI S4). May temperatures rank first for all catchments for the observation period 1961-2022. Specific sub-monthly periods of relative high temperatures occurred end of December and beginning of January, in March, May, June and July of the hydrological year 2022.

Annual precipitation amounts were 17 to 40% lower than the reference period, with the highest deficits for catchments in the Po basin (Figure SI S4). Especially the winter period stood out, with deficits up to 50% for catchments in the Po basin. Catchments in the Rhine basin showed the smallest deficits in winter ranging between 20-35%. In summer, the precipitation deficits ranged between 15 and 40% with less differences between the basins. The months with the highest deficits were March (mean deficit of 80% across all catchments), followed by January (59%), October (47%), July (46%) and May (41%). Periods without precipitation ($<$1 mm/d) for at least 10 days occurred several times in winter (in October, December, January, the whole month of March) and in Spring (April). During the summer, all catchments experienced a two-week dry period from around 5-19 July.

Over the whole spring and summer, streamflow was much below normal for the Rhine basin, with lowest ows occurring around mid-August. For the Rhone basin, ows were uctuating because of reservoir operations, but were in general close to normal conditions. Similar short-term stream ow uctuations are observable for the downstream reaches of the Po and Inn basins, but from April onward (Po basin) and June onward (Inn basin) stream ow was much lower than normal. Upstream, especially in the Rhone basin, stream ow was higher than normal, except for September. For other upstream catchments, stream ow was close to normal conditions, with higher ow periods in May and June in the Rhine upstream catchment, in May, June and July for the Rhone catchment, and in June, July and August for the Inn upstream catchment. The upstream catchment of the Po basin only showed a relative high ow at the end of July/beginning of August (Figure S4).

Figure S5: Daily glacier storage changes for 2022 for all glaciers in the four considered main basins expressed as glacier-speci c values. The thick lines represents the mean signal while the shaded area shows the min/max range for individual glaciers. Here we switched the signs of the glacier storage change values, with positive values representing storage release and melt contributions, while negative values represent glacier storage increase and accumulation. The latter is represented by the bar plot, aggregating the accumulation season from October-April, with the reference value represented by the empty bar, and the values of 2022 by the lled blue bar.

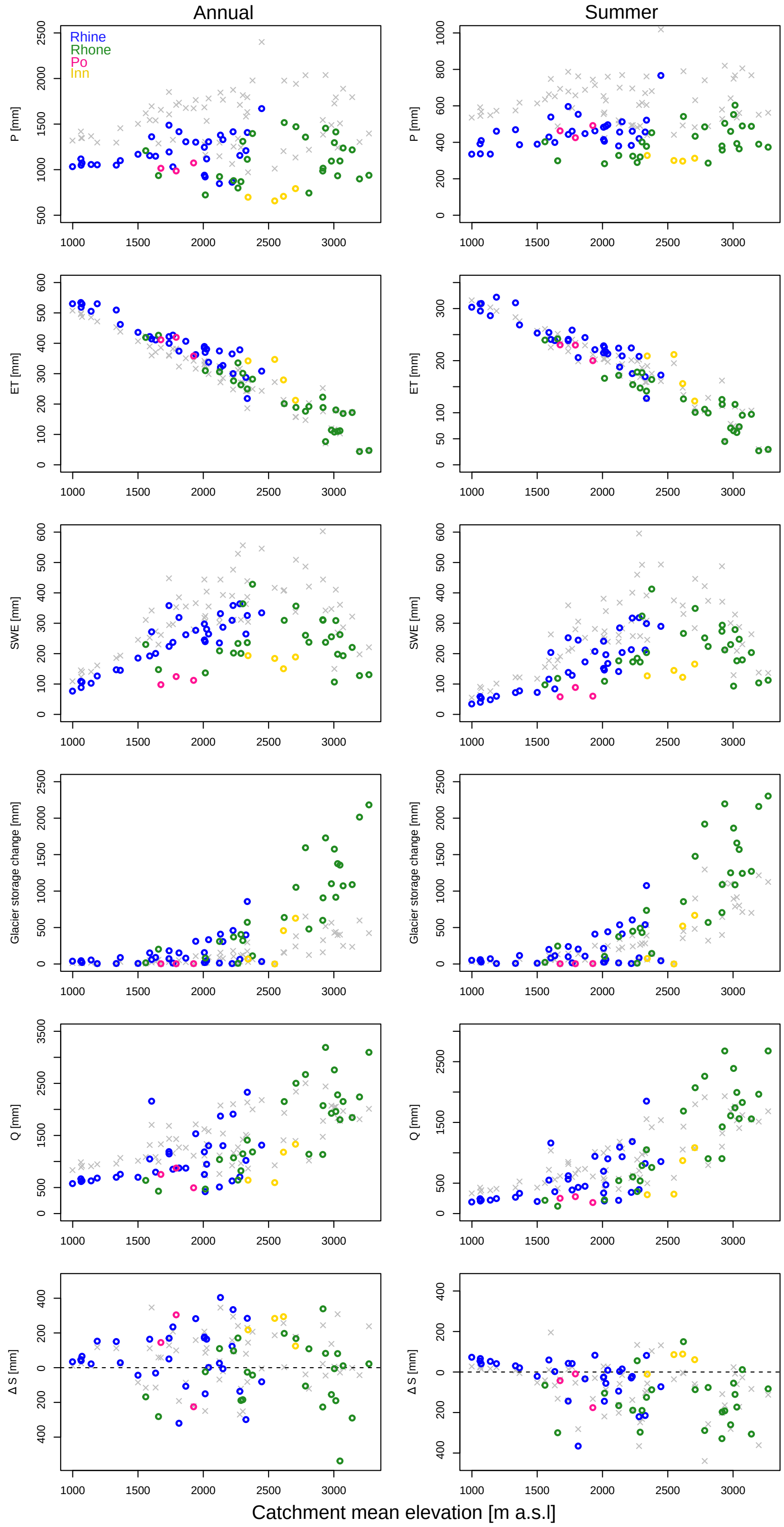

Figure S6: Water balance components for all catchments for the reference period (average of 1991-2020, gray crosses) and for 2022 (colors). Left column are annual values, while the right column shows the variables for the summer period (MJJA). Catchments are sorted according to catchment mean elevation (x-axis).

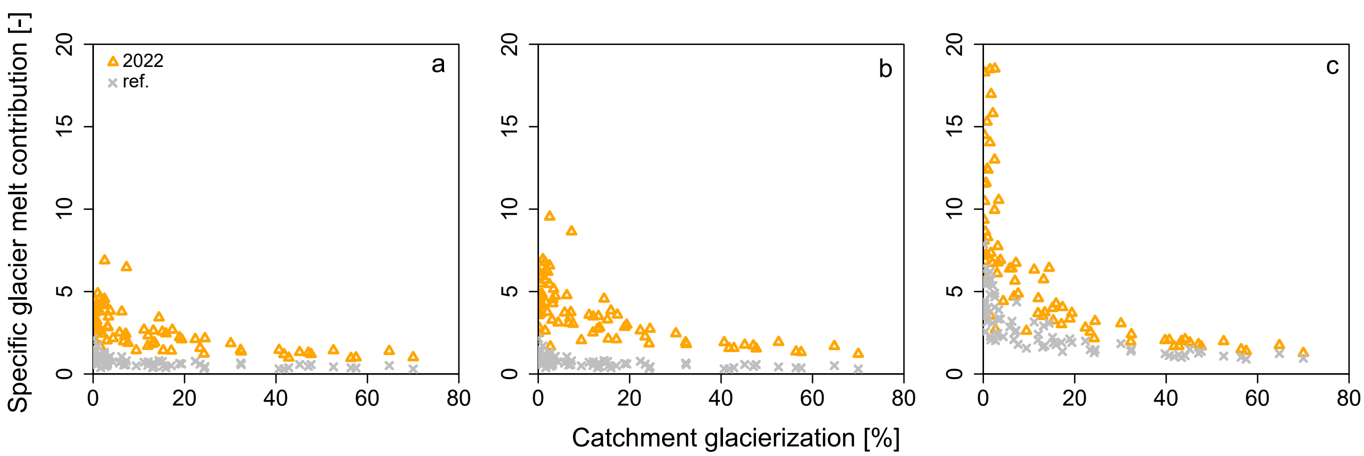

Figure S7: Specific glacier melt contributions to streamflow for a) imbalanced melt to annual streamflow, b) total melt to annual streamflow, and c) summer melt to summer streamflow. Specific contribution is here defined as the relative glacier melt contribution divided by the catchment relative glacier cover.