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Supplement of

Decadal in situ hydrological observations and empirical modeling of pressure head in a high-alpine, fractured calcareous rock slope

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Supplementary material

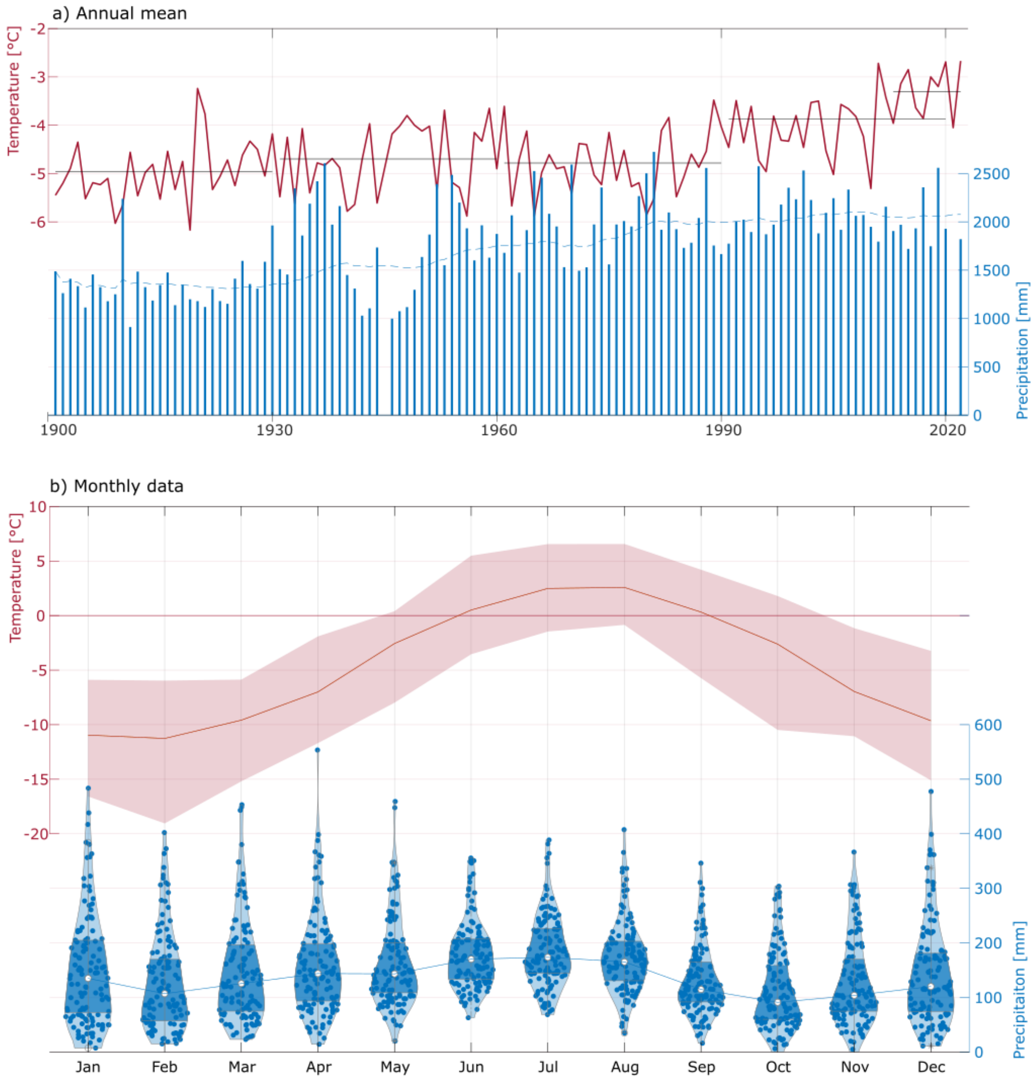
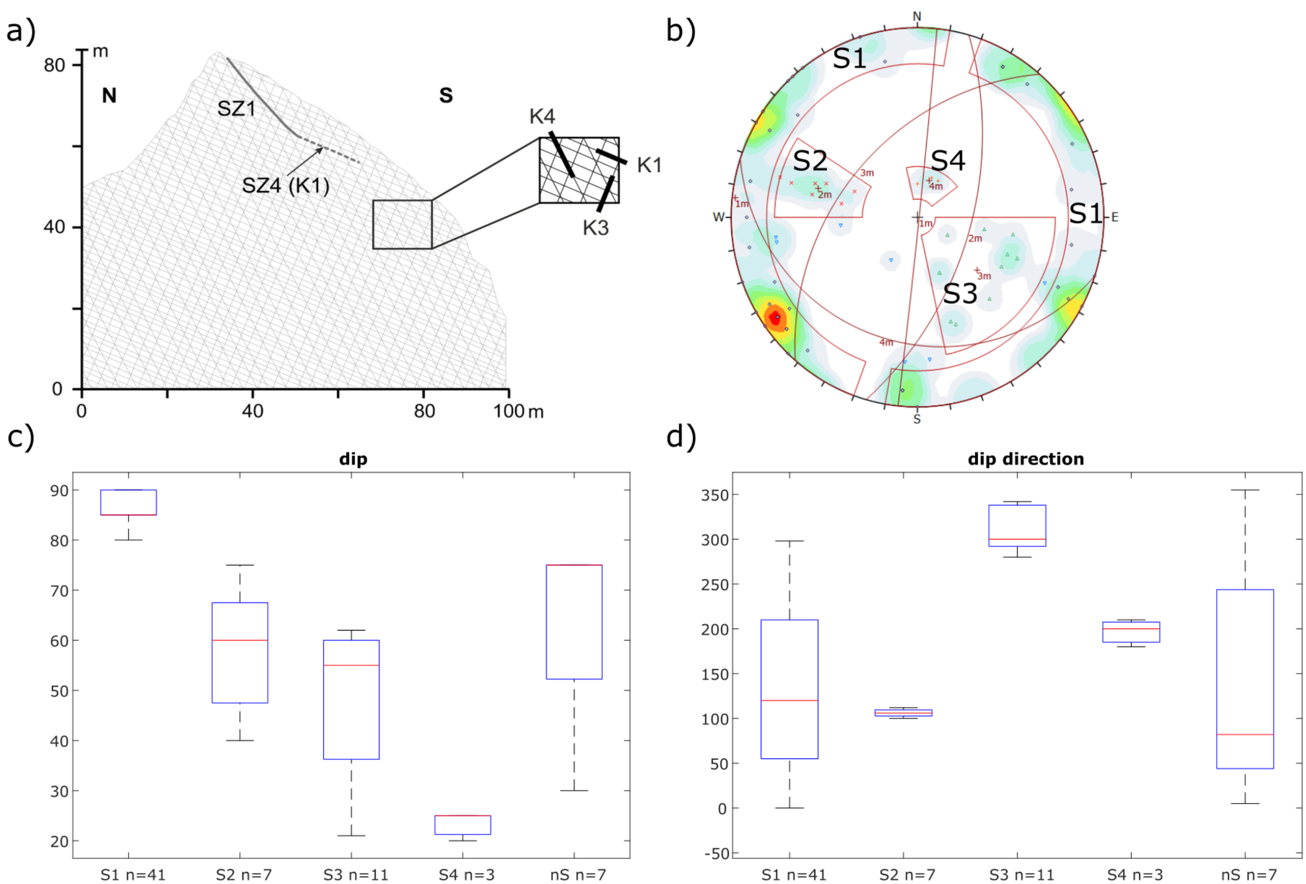


Figure S1. Long-term and seasonal temperature and precipitation patterns.

a) The red line represents the annual mean temperature, and the black lines are the respective averages of the selected period. It can be seen that the last 3 years have a drastical increase, and the last 10 years even more. Blue bars represent the annual precipitation, the blue line is the 30-year moving mean: no recent changes are visible.

b) Monthly data between 1901 and 2022. The average temperature is shown in red, with $\pm 2 \cdot standard deviation$. The blue violin plots represent the precipitation for each month using a kernel distribution that highlights the 1st and 3rd quantiles with darker blue and the median with a white point. Summer maximum, February and October minimum.



e)

Mamot et al. (2021)	K1	K2	K3	K4
Dip Mean (St. deviation)	24 (3)	69 (4)	66 (8)	63 (-)
Dip Direction Mean (SD)	175 (20)	293 (13)	126 (5)	130 (-)
Number of elements	15	21	37	20

This study	S1	S2	S3	S4
Mean Dip (SD)	86 (4)	58 (12)	49 (14)	23 (3)
Mean Dip Direction (SD)	129 (90)	106 (4)	311 (25)	197 (15)
Number of elements	41	7	11	3

Figure S2. Fracture mapping. a) NS-Profile of the Zugspitze Ridge with the instability analyzed in Mamot et al. (2021), with fractures from the external scan line, which is located 400m from the tunnel. b) Results from the underground scan line in the tunnel, presented in this study. c) and d) Dip and dip direction for the 5 clusters of the tunnel scan line in the tunnel. e) Numerical comparison of the two scan lines.

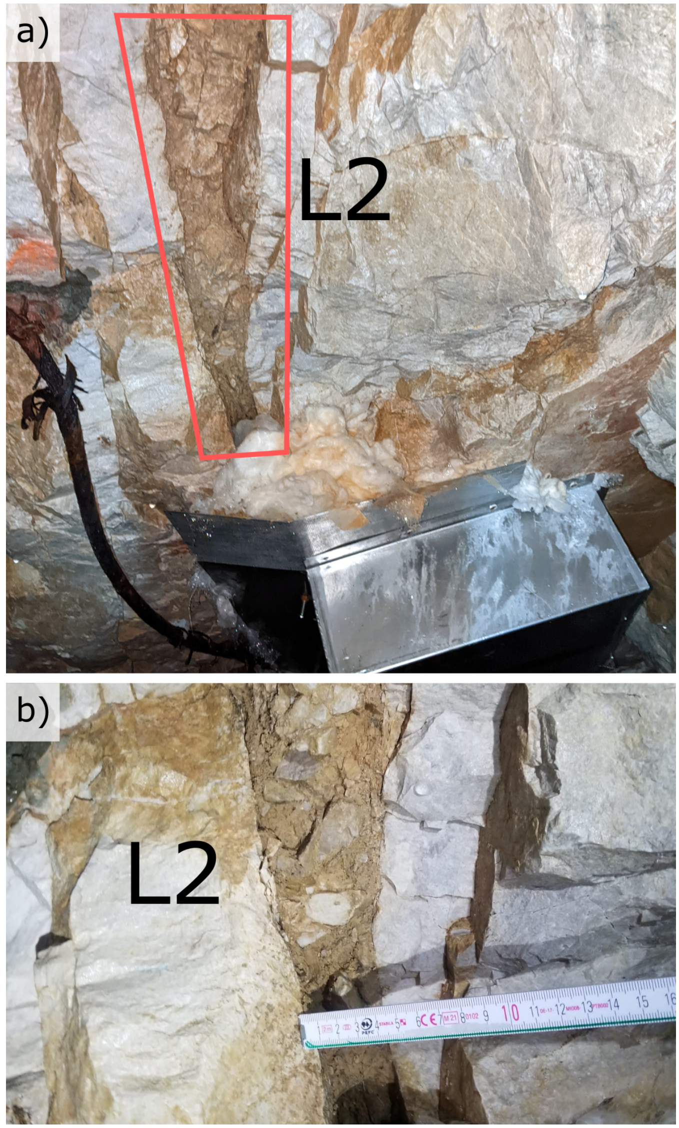


Figure S3. a) Picture of fracture L2. b) Measurement of fracture aperture.

Table S1. Parameters of the mean recession curve fitting.

Fitting	Flow component	α_x (or β_x) [1/h]	$Q0_x$ [l/h]	Error[1]
Linear	fast-flow / turbulent	$\beta_1 = 0.023$	$Q0_1 = 13.6$	4103 l
Exponential 1	slow-flow / laminar	$\alpha_1 = 0.109$	$Q0_1 = 41.9$	86 l
Exponential 2	slow-flow / laminar	$\alpha_1 = 0.015$ / $\alpha_2 = 0.123$	$Q0_1 = 1.8$ / $Q0_1 = 41.4$	17 l

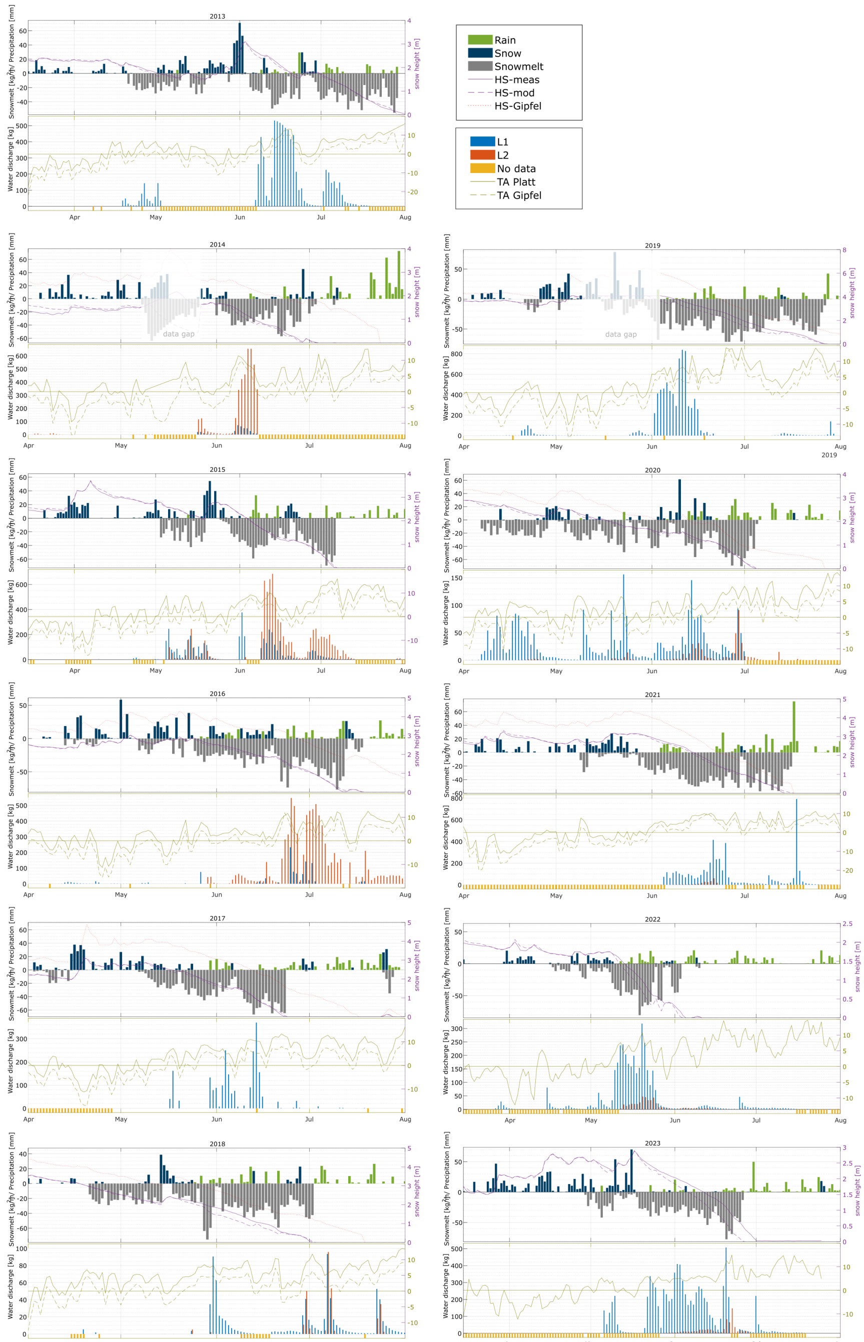


Figure S4. Snowmelt, daily values, all years.

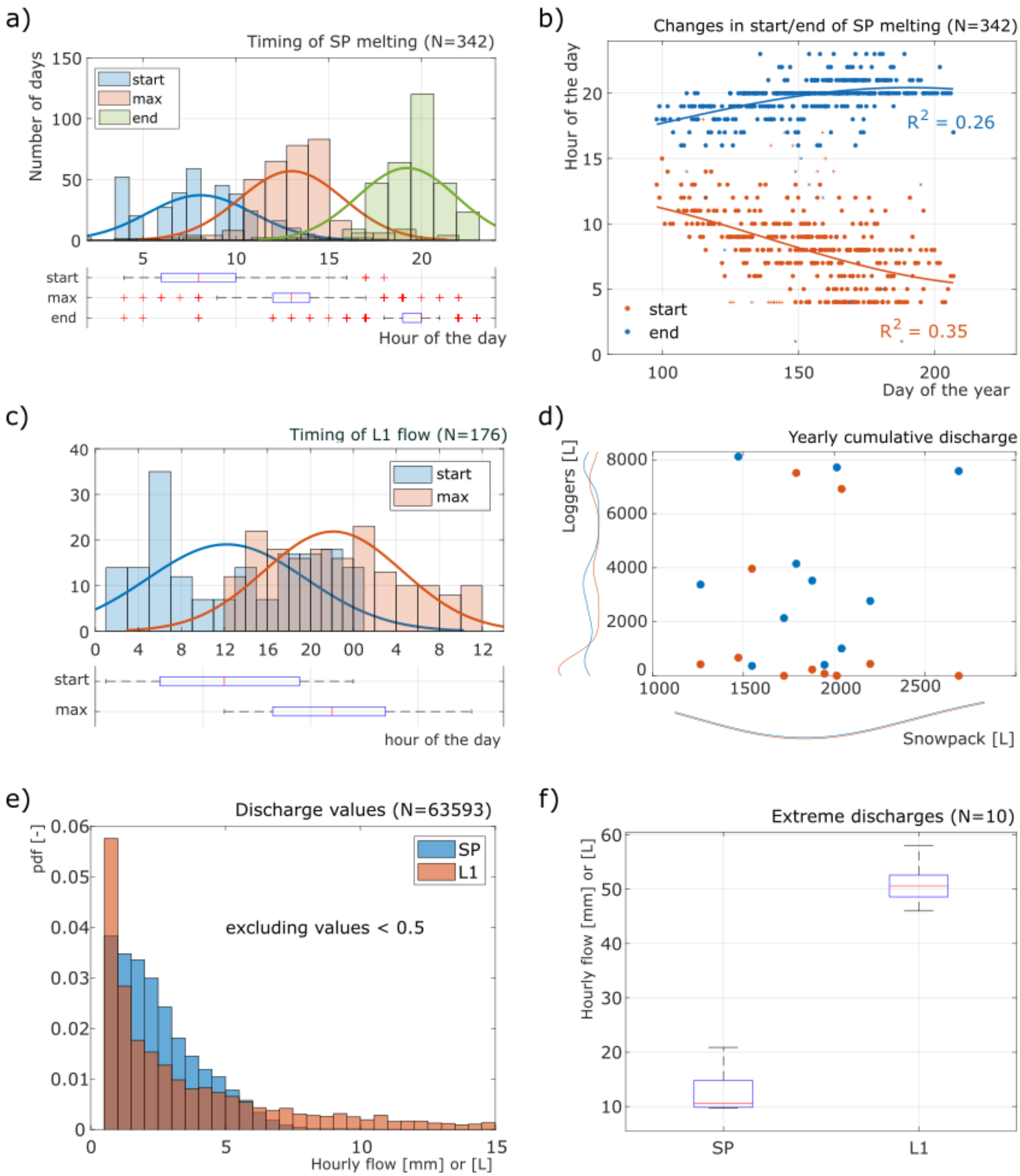


Figure S5. Additional statistics. a) Timing of start, peak flow, and end of snowmelt, with probability distributions and boxplots. b) Variability in the start and the end of melting during the season, fitting quite well with a sinus curve. High timing variability is due to daily different sun radiation, cloud cover and temperature. c) Timing of start and max flow in L1, with a probability distribution and boxplot. d) Sum of water flow for each year. e) Distribution of discharge values for the model, in blue, and for L1, in red. In both cases, there is a very high concentration of small values (<0.5 L or mm) that has been excluded. g) Ten maximum hourly discharge events for the model and for L1.

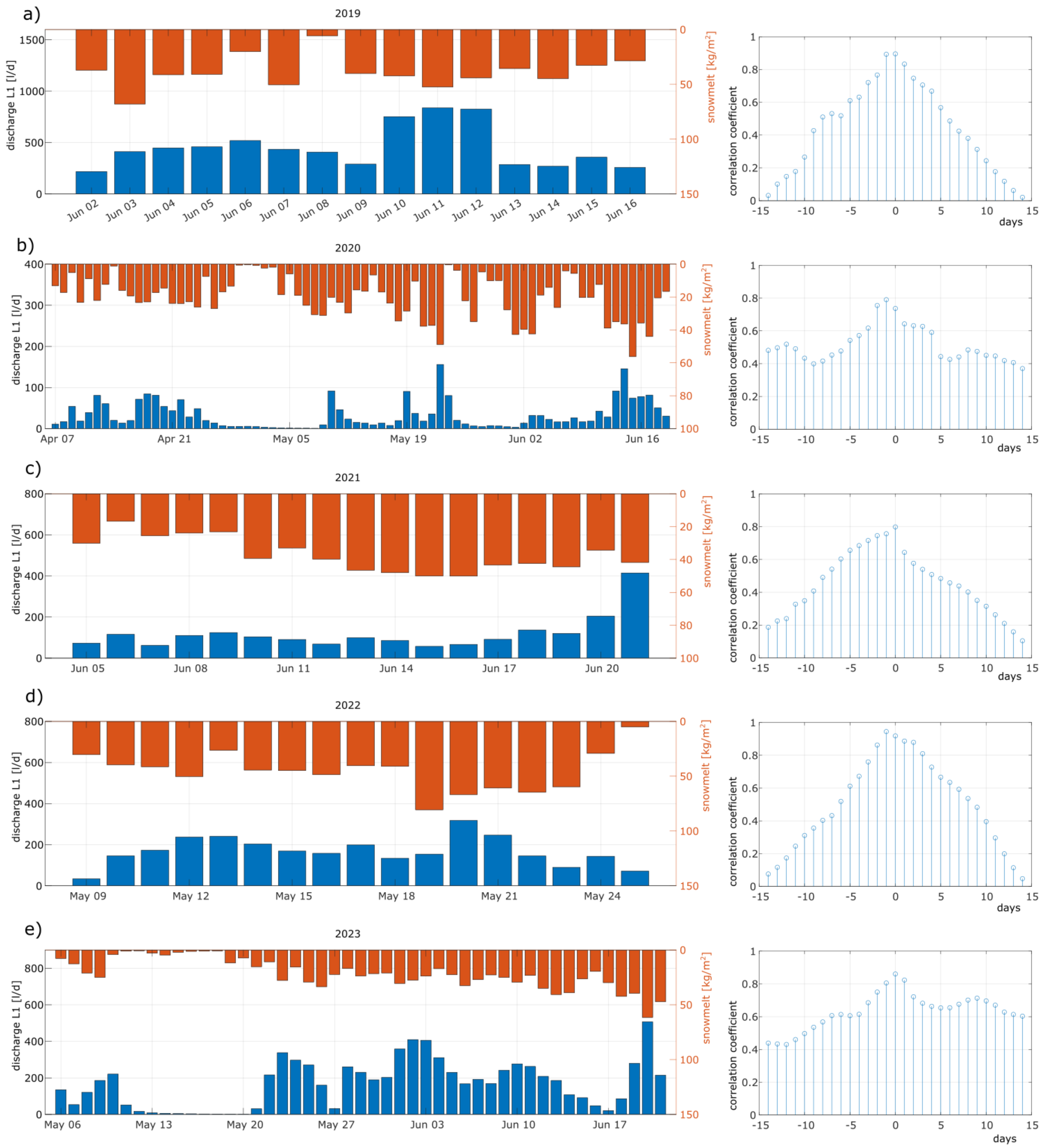


Figure S6. Daily correlation between snowmelt and water flow, from 2019 (a) to 2023 (e). On the left: Snowmelt in red and water flow in L1 in blue. On the right: results of the correlation for each single year.

START TIME					END TIME			DURATION			TOTAL					MAXIMUM			MAX 24		
PSUM	L1	L2	Delay R-L1 [h]	Delay R-L2 [h]	PSUM	L1	L2	PSUM [h]	L1 [h]	L2 [h]	PSUM [mm]	L1 [L]	L2 [L]	L1/ PSUM [-]	L2/ PSUM [-]	PSUM [mm/h]	L1 [L/h]	L2 [L/h]	PSUM [mm/d]	L1 [L/d]	L2 [L/d]
11/8/14 - 02	12/8/14 - 00	11/8/14 - 16	22	14	14/8/14 - 15	20/8/14 - 11	20/8/14 - 17	85	203	217	87	190	1338	2.2	15.4	6.8	5.3	15.9	47.9	75.5	347.5
15/8/15 - 13	16/8/15 - 20	16/8/15 - 20	31	31	19/8/15 - 11	22/8/15 - 21	24/8/15 - 07	94	145	179	104	464	1945	4.4	18.7	6.3	12.5	24.6	43.3	197.1	570.8
27/6/18 - 12	29/6/18 - 14	29/6/18 - 16	50	52	28/6/18 - 23	02/7/18 - 05	01/7/18 - 11	35	63	43	49	81	66	1.7	1.3	4.1	2.5	2.8	39.1	50.9	53.7
05/7/18 - 11	06/7/18 - 20	06/7/18 - 20	33	33	07/7/18 - 07	10/7/18 - 04	09/7/18 - 04	44	80	56	71	170	155	2.4	2.2	8.1	6.4	5.1	52.7	101.8	104.0
22/7/18 - 21	23/7/18 - 12	23/7/18 - 15	15	18	23/7/18 - 13	26/7/18 - 00	25/7/18 - 00	16	60	33	33	108	53	3.3	1.6	13.9	5.9	2.7	35.2	80.7	49.0
30/8/18 - 03	31/8/18 - 03	31/8/18 - 06	24	27	01/9/18 - 18	04/9/18 - 15	04/9/18 - 14	63	108	104	81	280	233	3.4	2.9	5.4	8.0	4.1	54.3	116.4	79.5
12/7/19 - 01	13/7/19 - 15	-	38	-	16/7/19 - 00	21/7/19 - 10	-	95	187	-	65	108	-	1.7	-	6.6	2.3	-	44.7	37.0	-
11/8/19 - 20	13/8/19 - 03	13/8/19 - 15	31	43	14/8/19 - 04	16/8/19 - 04	14/8/19 - 11	56	73	20	69	109	25	1.6	0.4	11.3	14.7	7.7	55.2	72.6	25.1
20/8/19 - 14	21/8/19 - 20		30	-	21/8/19 - 04	23/8/19 - 18	-	14	46	-	35	45	-	1.3	-	5.2	1.7	-	37.1	31.6	-
01/9/19 - 15	02/9/19 - 07	02/9/19 - 14	16	23	02/9/19 - 21	05/9/19 - 09	03/9/19 - 23	30	74	33	53	118	35	2.2	0.6	11.7	4.2	1.7	51.7	75.3	31.8
28/6/20 - 16	29/6/20 - 11	29/6/20 - 08	19	16	29/6/20 - 15	30/6/20 - 21	30/6/20 - 15	23	34	31	46	133	109	2.9	2.4	6.0	10.0	6.4	46.1	118.9	104.4
10/7/20 - 14	-	12/7/20 - 03	-	37	11/7/20 - 19		13/7/20 - 01	29	-	22	56	-	15	-	0.3	8.0	-	1.5	53.8		15.3
28/8/20 - 17	30/8/20 - 00	-	31	-	30/8/20 - 15	31/8/20 - 03	-	46	27	-	65	-	-	-	-	7.6	3.1	-	51.5	58.0	-
08/7/21 - 10	09/7/21 - 05	-	19	-	11/7/21 - 06	11/7/21 - 14	-	68	57	-	78	148	-	1.9	-	10.3	8.2	-	48.6	101.0	-
10/7/21 - 16	11/7/21 - 13	-	21	-	11/7/21 - 06	14/7/21 - 01	-	14	60	-	29	72	-	2.5	-	9.2	2.6	-	28.8	46.2	-
16/7/21 - 18	17/7/21 - 17	-	23	-	19/7/21 - 08	20/7/21 - 01	-	62	56	-	195	966	-	4.9	-	18.9	55.1	-	157.9	805.3	-
03/8/21 - 13	05/8/21 - 12	05/8/21 - 15	47	50	06/8/21 - 08	08/8/21 - 18	07/8/21 - 19	67	78	52	62	140	28	2.3	0.5	6.9	4.6	1.2	36.7	81.0	19.5
07/8/21 - 15	08/8/21 - 20	07/8/21 - 15	29	-	08/8/21 - 19	11/8/21 - 01	09/8/21 - 10	28	53	43	35	49	6	1.4	0.2	9.4	1.6	0.2	34.1	31.4	8.1
22/8/21 - 03	23/8/21 - 13	-	34	-	24/8/21 - 15	29/8/21 - 22	-	60	153	-	56	63	-	1.1	-	9.6	1.4	-	40.5	25.2	-
15/9/21 - 13	17/9/21 - 14	-	49	-	17/9/21 - 05	19/9/21 - 20	-	40	54	-	51	41	-	0.8	-	9.8	1.5	-	37.7	27.4	-
19/9/21 - 12	20/9/21 - 22	-	34	-	20/9/21 - 13	26/9/21 - 07	-	25	129	-	44	98	-	2.3	-	4.4	3.0	-	43.7	50.5	-
26/9/21 - 15	28/9/21 - 13	-	46	-	26/9/21 - 23	30/9/21 - 20	-	8	55	-	24	18	-	0.8	-	9.0	0.5	-	24.0	10.3	-
23/6/22 - 20	25/6/22 - 06	-	34	-	24/6/22 - 20	27/6/22 - 15	-	24	57	-	33	80	-	2.4	-	11.0	3.6	-	42.0	56.9	-

Figure S7. List of selected summer precipitation events with water flow in tunnel. All dates are expressed with the format "dd/m/yy - hh".

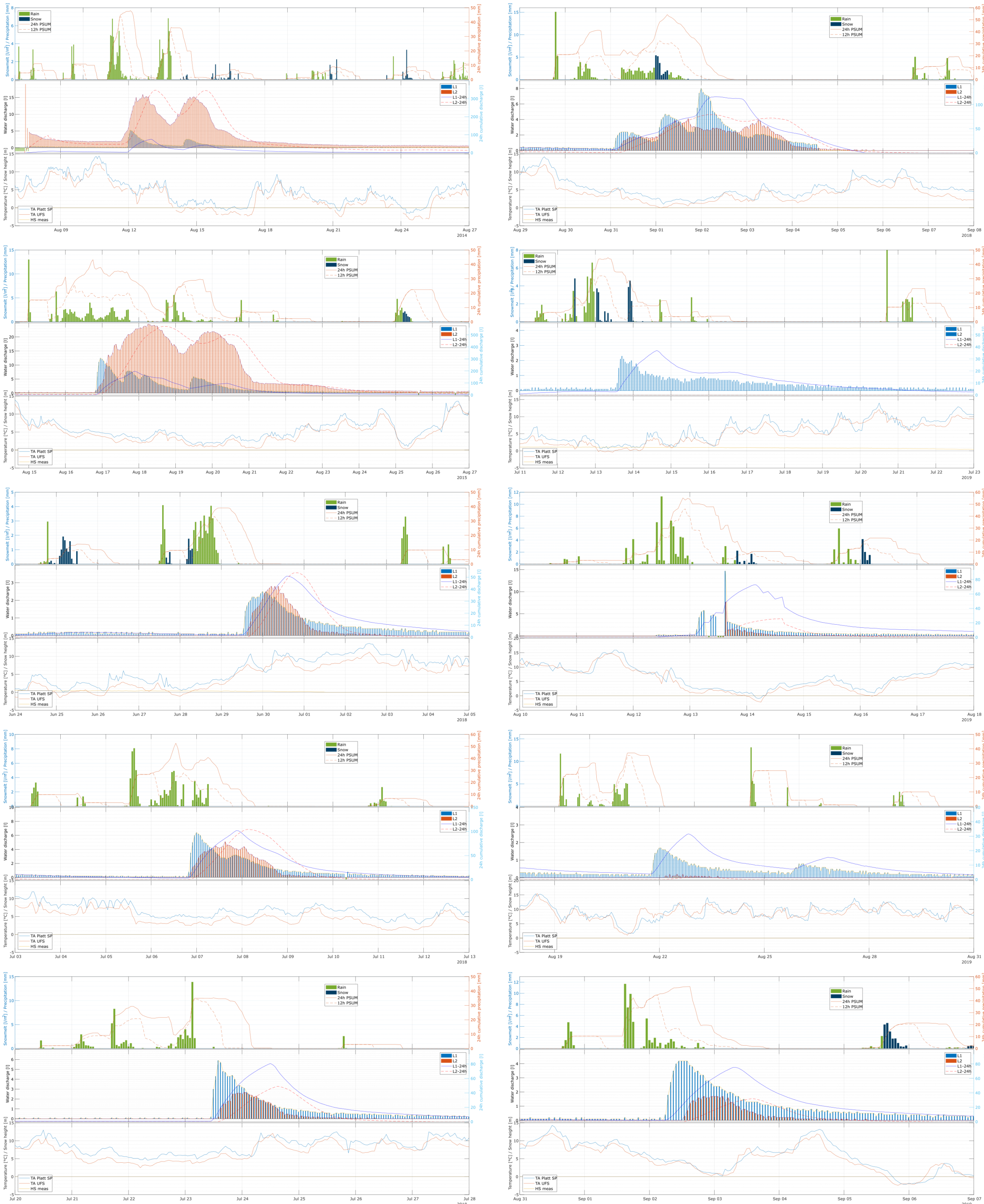


Figure S8. Summer precipitation events, hourly values - part 1

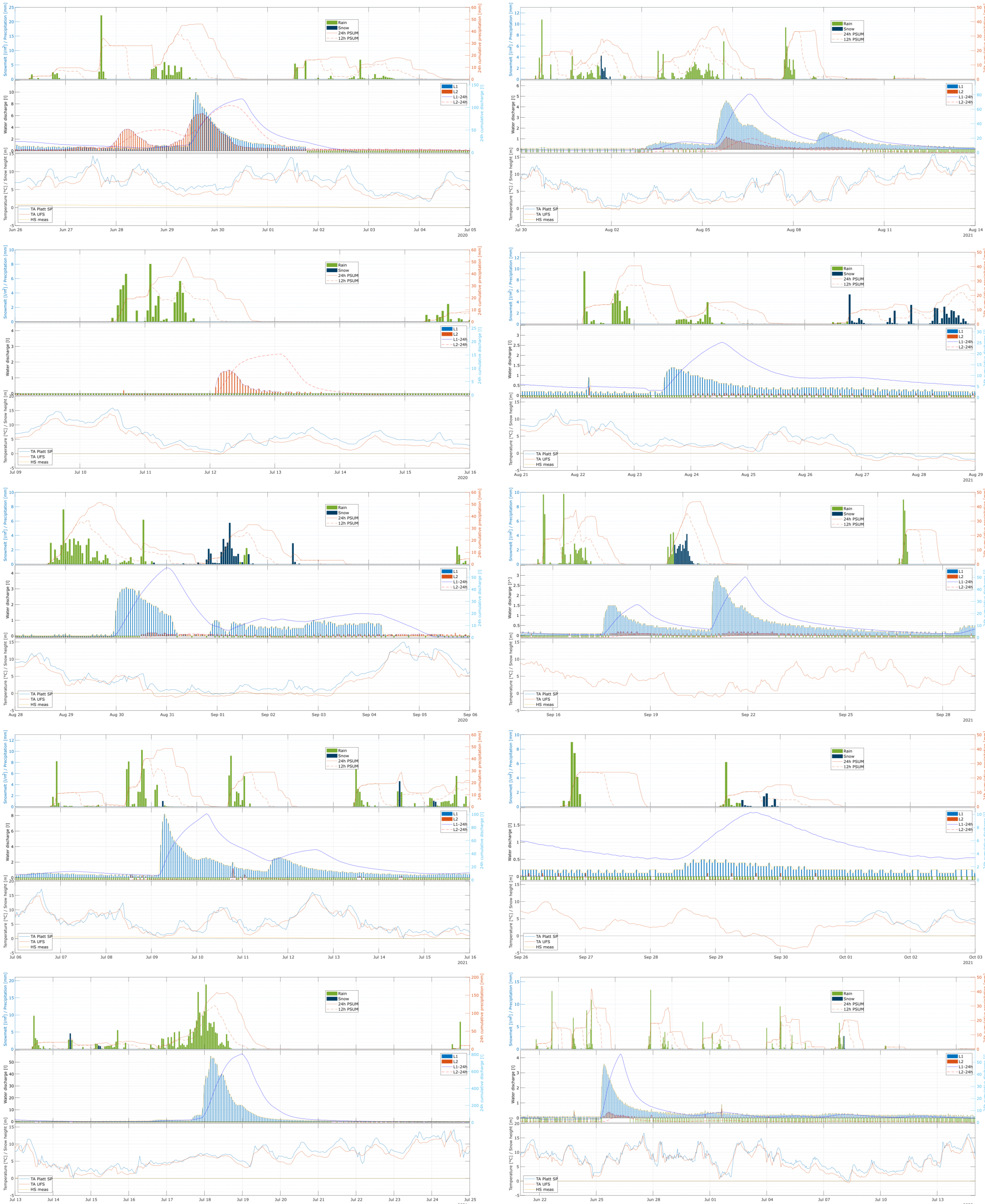


Figure S9. Summer precipitation events, hourly values - part 2

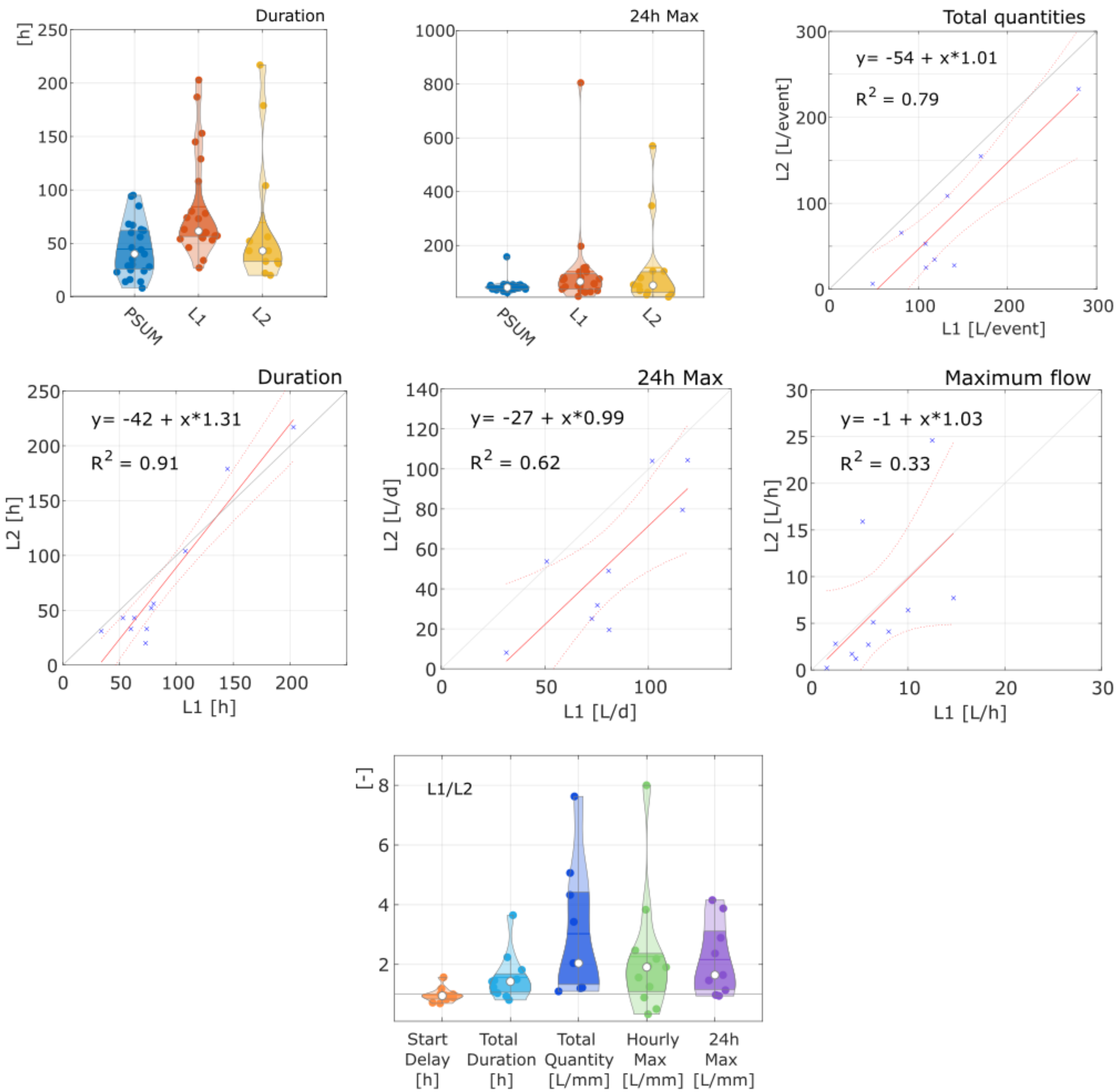


Figure S10. Violin plots for quantities (upper graphs) and ratios (lower graphs) for L1, L2, and P for the parameters duration, total quantity, maximum hourly flow, and maximum daily flow.

Start event	Stop event	Duration (h)	Total precipitation (mm)	Maximum precipitation (mm/h)
8/9/2014 3:00	8/9/2014 15:00	12:00:00	10.80	3.90
9/7/2014 16:00	9/7/2014 17:00	01:00:00	1.70	1.60
9/8/2014 17:00	9/8/2014 19:00	02:00:00	8.02	6.95
8/24/2015 22:00	8/25/2015 10:00	12:00:00	22.32	4.79
8/27/2015 7:00	8/27/2015 10:00	03:00:00	2.30	1.74
8/30/2015 17:00	8/30/2015 20:00	03:00:00	4.20	3.10
9/13/2015 20:00	9/14/2015 18:00	22:00:00	31.10	7.96
9/16/2015 1:00	9/16/2015 8:00	07:00:00	6.70	2.00
9/17/2015 16:00	9/17/2015 20:00	04:00:00	13.80	4.97
7/21/2016 8:00	7/21/2016 10:00	02:00:00	5.90	3.62
7/22/2016 16:00	7/22/2016 17:00	01:00:00	10.00	9.70
7/24/2016 18:00	7/24/2016 23:00	05:00:00	25.22	10.45
7/26/2016 14:00	7/26/2016 20:00	06:00:00	14.16	11.70
7/28/2016 19:00	7/29/2016 6:00	11:00:00	10.48	3.51
8/2/2016 20:00	8/3/2016 6:00	10:00:00	4.30	1.34
8/15/2016 10:00	8/15/2016 12:00	02:00:00	5.14	4.44
8/18/2016 1:00	8/18/2016 2:00	01:00:00	3.04	2.82
8/18/2016 19:00	8/19/2016 2:00	07:00:00	4.05	1.65
7/28/2018 22:00	7/29/2018 2:00	04:00:00	11.79	4.51
8/1/2018 19:00	8/1/2018 21:00	02:00:00	2.86	2.38
8/2/2018 19:00	8/2/2018 21:00	02:00:00	4.21	2.14
8/12/2018 19:00	8/12/2018 21:00	02:00:00	4.00	3.96
8/13/2018 12:00	8/15/2018 0:00	36:00:00	34.19	9.55
8/18/2018 14:00	8/18/2018 22:00	08:00:00	9.58	6.80
8/19/2018 13:00	8/19/2018 16:00	03:00:00	9.15	4.62
8/21/2018 15:00	8/21/2018 16:00	01:00:00	0.78	0.78
8/23/2018 12:00	8/23/2018 21:00	09:00:00	32.17	15.58
7/20/2019 17:00	7/21/2019 10:00	17:00:00	23.11	10.13
7/27/2019 12:00	7/27/2019 14:00	02:00:00	24.06	14.75
8/24/2019 15:00	8/24/2019 18:00	03:00:00	24.76	13.13
8/28/2019 17:00	8/29/2019 0:00	07:00:00	9.98	3.23
8/31/2019 16:00	8/31/2019 20:00	04:00:00	10.38	4.75
7/13/2021 11:00	7/13/2021 19:00	08:00:00	18.97	9.76
7/24/2021 13:00	7/24/2021 19:00	06:00:00	10.00	8.01
7/27/2021 23:00	7/28/2021 15:00	16:00:00	8.88	3.45
7/30/2021 14:00	7/31/2021 1:00	11:00:00	18.67	10.80
9/9/2021 15:00	9/10/2021 0:00	09:00:00	3.09	2.80
9/10/2021 22:00	9/11/2021 2:00	04:00:00	22.37	7.96
6/5/2022 13:00	6/5/2022 17:00	04:00:00	8.24	3.54
6/12/2022 23:00	6/13/2022 10:00	11:00:00	14.13	2.66
6/16/2022 8:00	6/16/2022 11:00	03:00:00	11.22	6.11
6/21/2022 18:00	6/21/2022 23:00	05:00:00	3.76	2.21
6/22/2022 16:00	6/22/2022 17:00	01:00:00	12.93	12.93
6/23/2022 18:00	6/23/2022 22:00	04:00:00	14.68	6.99
6/27/2022 18:00	6/27/2022 22:00	04:00:00	18.04	13.19
6/28/2022 12:00	6/28/2022 20:00	08:00:00	11.73	3.83
6/30/2022 14:00	7/1/2022 14:00	24:00:00	17.38	6.07
7/3/2022 23:00	7/5/2022 9:00	34:00:00	27.35	9.52
7/7/2022 19:00	7/8/2022 3:00	08:00:00	19.37	5.88

Table S2. List of selected summer precipitation events with NO water flow in tunnel.

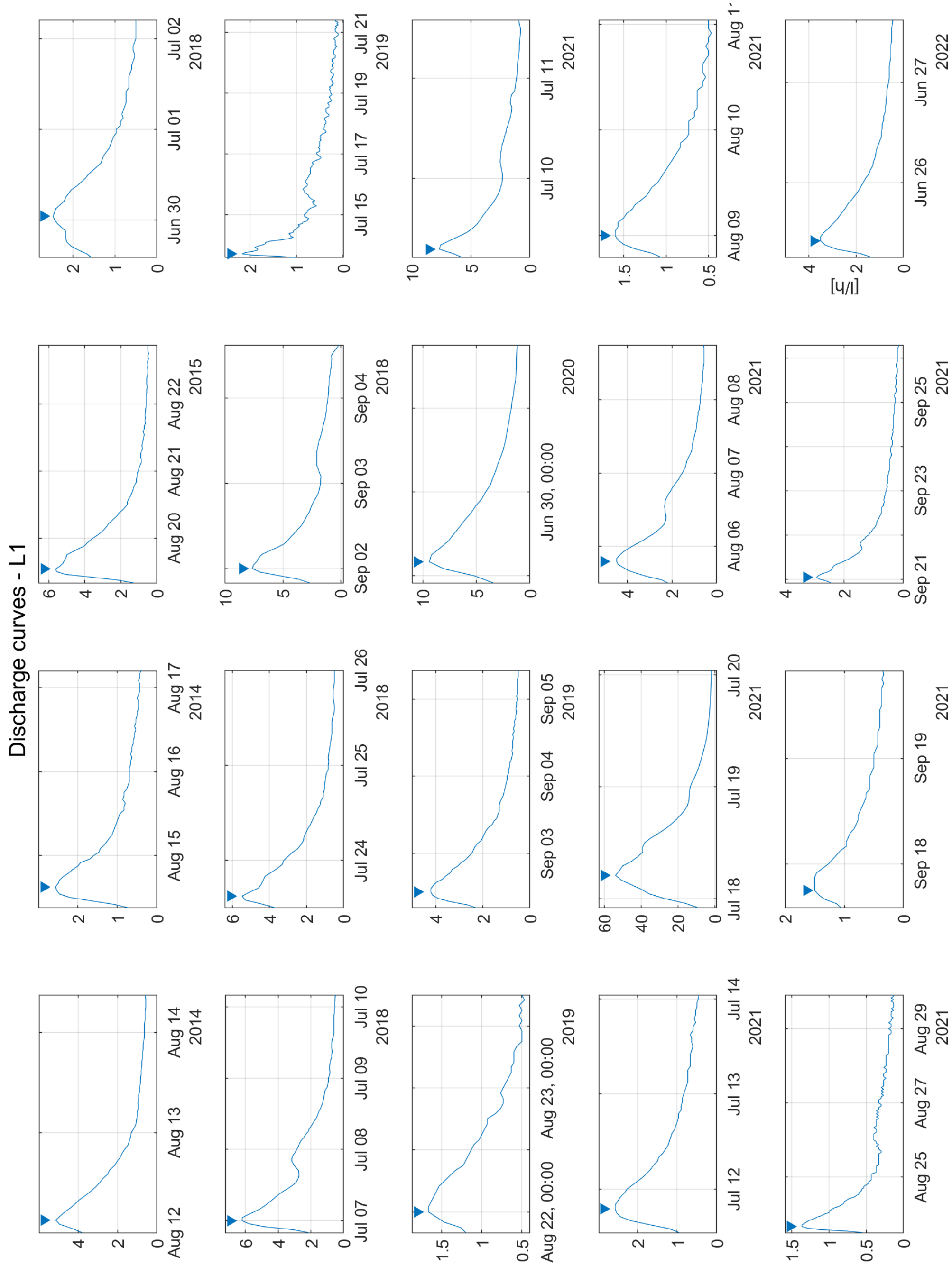


Figure S11. Discharge curves L1

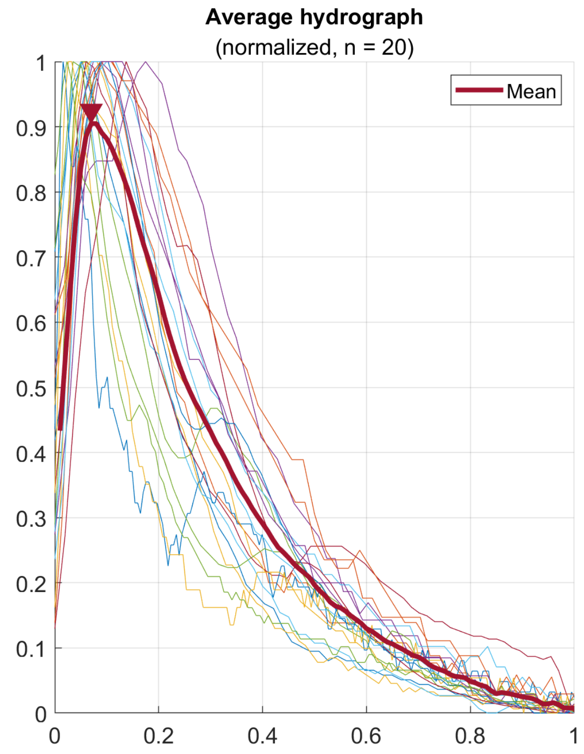


Figure S12. Normalized discharge curves for gauge L1, the mean value of the curves is shown in red.

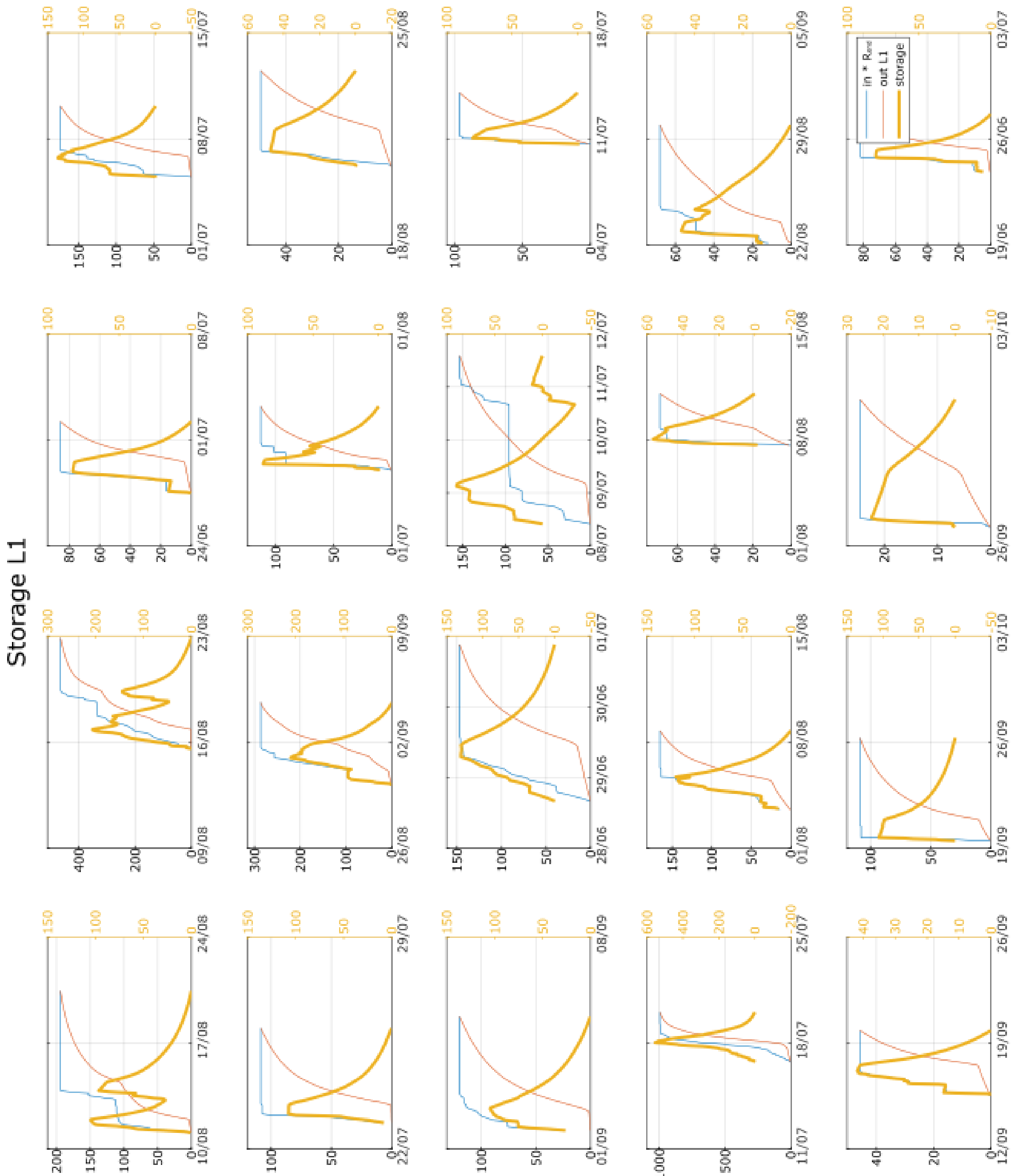


Figure S13. Storage curves for L1. Each graph represents one event: in blue, the cumulative input (precipitation); in red, the cumulative output (gauge L1 or L2); and in yellow, the water that can accumulate into the rock at each hour. The total inflow in every event is forced to be equal to the total outflow, with the help of the multiplication factor *R*.

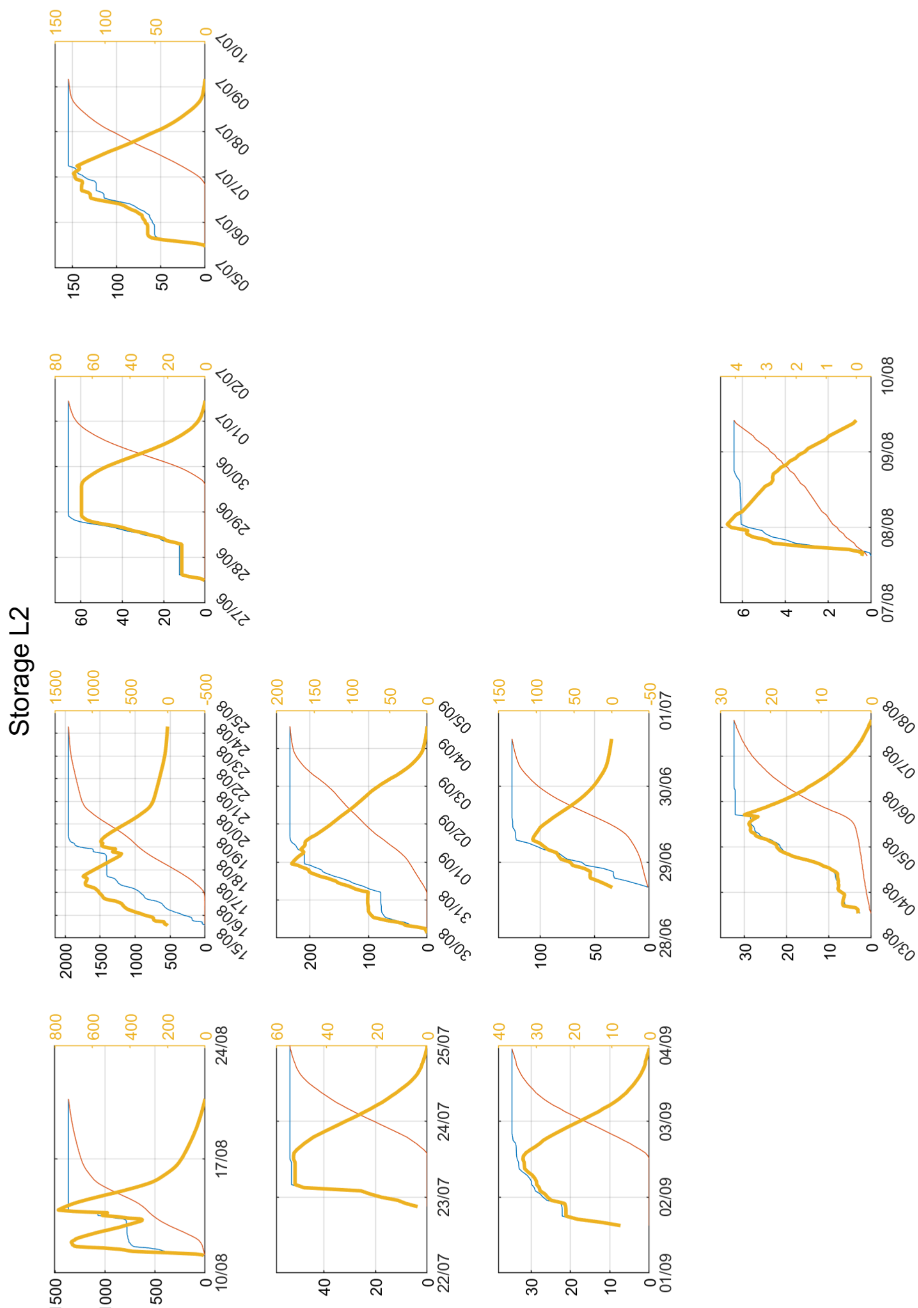


Figure S14. Storage curves for L2. See the picture before for explanations.

K [m/s]	L [m]	t [h]	H1 [m]
1.E-05	1.1	200	69.61
1.E-05	1.2	200	40.34
1.E-05	1.3	200	25.43
1.E-05	1.4	200	17.12
1.E-05	1.5	200	12.15
5.E-05	5.5	200	69.61
5.E-05	5.75	200	52.37
5.E-05	6.1	200	36.56
5.E-05	6.5	200	25.43
5.E-05	7.5	200	12.15
1.E-04	11	200	69.61
1.E-04	11.5	200	52.37
1.E-04	12	200	40.34
1.E-04	13	200	25.43
1.E-04	15	200	12.15
1.5.E-04	16.5	200	69.61
1.5.E-04	18	200	40.34
1.5.E-04	19.5	200	25.43
1.5.E-04	21	200	17.12
1.5.E-04	22.5	200	12.15
2.0.E-04	22	200	69.61
2.0.E-04	24	200	40.34
2.0.E-04	26	200	25.43
2.0.E-04	28	200	17.12
2.0.E-04	30	200	12.15

K [m/s]	L [m]	t [h]	H1 [m]
1.E-04	11.5	75	1.05
1.E-04	11.5	100	2.29
1.E-04	11.5	150	10.95
1.E-04	11.5	170	20.47
1.E-04	11.5	185	32.74
1.E-04	11.5	200	52.37
1.E-04	12	75	0.95
1.E-04	12	100	2.01
1.E-04	12	150	9.00
1.E-04	12	170	16.40
1.E-04	12	185	25.72
1.E-04	12	200	40.34
1.E-04	12.5	75	0.87
1.E-04	15.5	100	1.02
1.E-04	12.5	150	7.52
1.E-04	12.5	170	13.38
1.E-04	12.5	185	20.60
1.E-04	12.5	200	31.73
1.E-04	13	75	0.80
1.E-04	13	103	1.73
1.E-04	13	150	6.37
1.E-04	13	170	11.08
1.E-04	13	185	16.79
1.E-04	13	200	25.43

Table S3. Left table: possible couples of K and L that produce the same hydraulic head. In green are the feasible results, and in red are the values that are not realistic. Right table: testing different event lengths.