Estimation of recharge in mountain hard-rock aquifers based on discrete spring discharge monitoring during base-flow recession

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S1. Discharge, temperature and electric conductivity measurements at the springs of Mt. Prinzera and Mt. Zirone

		P01			P02			P03			P04			P05			P06			P07			days after previous measure
		Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	
Fall	25/10/2012	0.666	12.6	372	0.302	13.1	395	0.165	12.0	372	0.038	13.2	540	0.153	13.1	311	0.037	12.4	310	0.069	14.2	322	\
	27/10/2012	0.915	12.5	408	0.650	13.2	427	0.163	12.0	377	0.140	13.0	636	0.190	13.0	364	0.043	12.3	307	0.110	13.8	373	2
	30/10/2012	1.652	12.0	446	0.517	13.2	354	0.530	11.8	350	0.138	12.0	624	0.846	13.2	373	0.041	12.1	316	0.093	12.9	366	3
	02/11/2012	2.272	11.9	454	0.524	13.4	347	0.688	11.8	347	0.191	12.5	592	0.660	13.4	351	0.040	12.3	312	0.111	12.6	365	3
	06/11/2012	2.350	11.7	457	0.479	13.3	355	0.540	11.7	344	0.184	12.8	540	0.734	13.4	355	0.039	12.3	314	0.103	12.9	360	4
	09/11/2012	1.953	11.5	449	0.353	13.2	370	0.363	11.7	345	0.172	12.4	511	0.390	13.2	331	0.038	12.1	313	0.097	12.5	344	3
	16/11/2012	2.126	11.4	444	0.575	13.1	384	0.464	11.6	353	0.241	12.2	541	0.511	13.0	343	0.042	12.2	315	0.120	12.1	368	7
	24/11/2012	2.108	11.2	400	0.217	13.0	374	0.233	11.7	333	0.146	12.0	459	0.242	12.7	288	0.060	12.4	318	0.089	11.9	309	8
	30/11/2012	5.240	11.1	419	0.379	12.9	357	0.420	11.5	346	0.200	11.0	482	0.872	12.6	308	0.042	12.2	304	0.142	11.3	378	6
	03/12/2012	4.490	10.9	418	0.532	12.8	375	0.520	11.5	337	0.320	10.5	515	1.100	12.4	350	0.051	12.1	310	0.150	10.6	383	3
	11/12/2012	3.660	10.5	407	0.433	12.7	366	0.340	11.6	346	0.210	9.5	486	0.754	12.1	311	0.041	12.1	306	0.131	10.0	373	8
	23/12/2012	2.892	10.4	378	0.117	12.6	384	0.180	11.6	357	0.100	10.7	466	0.213	11.8	296	0.036	12.0	304	0.076	9.5	315	12
	29/12/2012	2.187	10.3	368	0.099	12.4	380	0.141	11.6	354	0.089	10.3	459	0.130	11.5	286	0.035	12.0	304	0.068	9.5	312	6
Fall average		2.501	11.4	417	0.398	13.0	374	0.365	11.7	351	0.167	11.7	527	0.523	12.7	328	0.042	12.2	310	0.105	11.8	351	
Winter	05/01/2013	2.296	10.3	368	0.091	12.3	370	0.131	11.7	346	0.081	11.0	444	0.260	11.7	297	0.037	12.1	301	0.090	9.4	344	7
	12/01/2013	2.218	10.3	355	0.087	12.1	366	0.128	11.7	340	0.057	9.6	436	0.103	11.4	280	0.035	11.9	305	0.084	9.5	318	7
	18/01/2013	2.018	10.0	353	0.148	12.1	346	0.240	11.7	350	0.113	8.9	446	0.530	11.2	330	0.039	11.9	308	0.096	9.0	322	6
	25/01/2013	2.934	10.1	389	0.219	12.2	359	0.403	11.7	360	0.169	9.6	457	0.801	11.0	350	0.042	11.9	312	0.115	8.7	332	7
	31/01/2013	2.703	10.0	394	0.212	12.4	331	0.316	11.6	337	0.272	10.5	472	0.700	10.2	313	0.040	11.7	289	0.050	8.5	317	6
	09/02/2013	4.193	9.8	377	0.156	12.2	320	0.364	11.6	319	0.237	10.2	423	0.332	9.1	284	0.038	11.6	285	0.018	7.9	295	9
	16/02/2013	3.306	9.6	364	0.134	12.1	313	0.292	11.6	310	0.210	10.0	412	0.229	9.0	270	0.037	11.5	280	0.017	6.7	292	7
	22/02/2013	2.083	9.5	344	0.113	11.9	322	0.189	11.5	316	0.174	9.1	407	0.356	8.9	303	0.038	11.3	297	0.030	5.6	310	6
	28/02/2013	1.945	9.6	365	0.190	12.1	335	0.220	11.5	342	0.209	10.2	423	0.488	9.0	317	0.039	11.6	295	0.018	5.6	307	6
	08/03/2013	5.156	9.9	389	0.254	12.3	324	0.512	11.6	334	0.365	10.6	431	0.713	8.7	343	0.044	11.7	292	0.020	6.1	314	8
	15/03/2013	4.746	9.8	374	0.236	12.3	319	0.353	11.5	340	0.248	10.8	425	0.553	7.9	305	0.042	11.4	293	0.015	6.7	305	7
	19/03/2013	5.597	9.8	388	0.397	12.1	350	0.731	11.5	353	0.624	11.0	434	0.923	8.0	321	0.048	11.5	300	0.020	6.9	317	4
	22/03/2013	4.395	9.8	377	0.321	12.1	291	0.646	11.5	324	0.548	11.2	425	0.776	8.1	297	0.043	11.7	295	0.011	7.8	313	3
	29/03/2013	5.899	9.7	368	0.274	12.1	310	0.382	11.4	315	0.359	10.9	413	0.760	7.6	273	0.042	11.5	292	0.010	7.4	303	7
Win. Average		3.535	9.9	372	0.202	12.2	333	0.351	11.6	335	0.262	10.3	432	0.537	9.4	306	0.040	11.7	296	0.042	7.6	314	
Spring	03/04/2013	6.400	10.2	384	0.423	12.1	284	0.670	11.4	319	0.520	11.5	416	1.010	7.8	287	0.043	11.4	302	0.012	8.5	313	5
	06/04/2013	6.532	10.0	384	0.514	12.0	301	0.751	11.4	323	0.680	11.0	419	1.110	7.2	295	0.044	11.4	306	0.014	7.9	320	3
	10/04/2013	5.569	10.2	386	0.347	12.0	290	0.390	11.4	318	0.530	12.0	413	0.900	7.3	263	0.042	11.3	302	0.011	9.5	306	4
	13/04/2013	6.092	10.4	384	0.279	12.1	305	0.330	11.5	324	0.420	12.1	423	0.556	7.4	258	0.040	11.3	300	0.013	9.8	308	3
	16/04/2013	7.023	10.6	382	0.211	12.1	321	0.272	11.5	331	0.320	12.1	434	0.213	7.6	251	0.038	11.3	307	0.014	12.0	311	3
	19/04/2013	5.112	10.7	377	0.185	12.2	329	0.232	11.5	335	0.267	12.5	436	0.134	7.8	252	0.037	11.2	310	0.052	12.8	312	3
	23/04/2013	4.184	10.8	375	0.194	12.2	326	0.216	11.5	336	0.178	12.1	444	0.464	7.6	254	0.041	11.0	308	0.051	12.1	310	4
	26/04/2013	3.673	10.9	374	0.189	12.2	329	0.221	11.5	333	0.172	13.2	447	0.420	8.6	256	0.042	11.0	307	0.045	13.3	309	3
	30/04/2013	3.302	11.1	373	0.184	12.2	332	0.227	11.5	336	0.166	12.6	450	0.375	8.3	258	0.043	11.1	306	0.040	12.7	307	4
	04/05/2013	3.061	11.1	370	0.168	12.2	338	0.199	11.6	341	0.154	13.6	457	0.270	8.9	255	0.041	11.1	307	0.027	13.7	305	4
	09/05/2013	3.358	11.3	375	0.154	12.2	344	0.171	11.6	346	0.143	12.9	465	0.175	8.4	253	0.039	11.0	308	0.015	14.9	302	5
	15/05/2013	3.179	11.4	367	0.140	12.3	349	0.153	11.6	349	0.137	12.4	458	0.170	8.4	260	0.038	11.0	301	0.014	15.1	299	6
	19/05/2013	3.425	11.4	366	0.182	12.2	331	0.204	11.6	343	0.132	12.3	463	0.478	8.6	260	0.044	11.2	302	0.015	14.2	301	4
	23/05/2013	2.940	11.3	366	0.170	12.1	334	0.193	11.5	344	0.123	12.3	477	0.287	8.6	250	0.042	11.2	303	0.014	13.9	297	4
	28/05/2013	2.466	11.3	366	0.159	12.1	338	0.182	11.5	345	0.114	12.4	487	0.274	8.7	241	0.039	11.2	305	0.014	13.7	294	5
	04/06/2013	2.207	11.4	363	0.150	12.3	345	0.130	11.7	361	0.099	13.0	491	0.122	8.9	238	0.037	11.3	303	0.014	14.1	291	7
	12/06/2013	1.939	11.5	360	0.138	12.4	353	0.096	11.8	367	0.079	12.8	497	0.074	9.0	234	0.036	11.3	301	0.014	14.5	289	8
	20/06/2013	1.663	11.6	357	0.124	12.7	359	0.079	12.0	370	0.061	13.5	502	0.060	9.9	230	0.033	11.5	298	0.013	15.7	287	8
	29/06/2013	1.419	11.3	355	0.108	12.6	364	0.061	12.1	374	0.084	13.3	506	0.054	10.2	224	0.032	11.7	299	0.013	15.2	284	9
Spr. Average		3.871	11.0	372	0.212	12.2	330	0.251	11.6	342	0.230	12.5	457	0.376	8.4	254	0.040	11.2	304	0.021	12.8	302	
Summer	04/07/2013	1.156	11.4	341	0.096	12.7	373	0.054	12.3	380	0.041	13.8	508	0.042	10.8	221	0.031	11.9	297	0.013	16.0	282	5
	12/07/2013	0.958	11.6	348	0.088	12.9	386	0.039	12.4	393	0.034	15.2	513	0.030	11.2	218	0.030	12.0	295	0.012	16.6	280	8
	14/07/2013	0.892	11.7	345	0.103	13.0	388	0.043	12.5	402	0.059	16.7	518	0.053	12.2	222	0.030	12.0	297	0.013	17.6	285	2
	21/07/2013	0.845	11.9	343	0.093	13.1	386	0.035	12.6	397	0.028	15.7	514	0.125	12.8	219	0.029	12.2	295	0.013	17.7	283	7
	28/07/2013	0.784	12.0	341	0.083	13.4	383	0.028	12.9	392	0.021	15.9	509	0.088	13.0	218	0.029	12.0	294	0.012	17.5	280	7
	18/08/2013	0.676	12.2	340	0.066	13.5	380	0.023	12.8	386	0.012	16.5	498	0.052	13.2	215	0.028	11.7	291	0.011	18.2	278	21
	28/08/2013	0.625	12.5	338	0.057	13.8	378	0.020	13.0	383	0.010	17.9	493	0.043	13.4	214	0.027	11.4	290	0.010	19.0	276	10
Sum. Average		0.848	11.9	342	0.084	13.2	382	0.035	12.6	390	0.029	16.0	508	0.062	12.4	218	0.029	11.9	294	0.012	17.5	281	
Year Average		3.060	10.9	379	0.240	12.5	348	0.279	11.7	348	0.198	12.1	474	0.417	10.2	282	0.039	11.7	302	0.047	11.8	315	

Table S1 – Discharge (Q), temperature (T) and electrical conductivity (EC) measurements at the springs of Mt. Prinzera along the hydrogeologic year 2012-2013 (the Q measures selected for summer recession analysis are highlighted in red).

		Z01			Z02			Z03			Z04			Z05			
		Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	Q [l/s]	T [°C]	EC [µS/cm]	days after previous measure
Fall	17/10/2016	0.135	12.1	333	0.111	12.4	644	0.800	8.9	420	0.907	11.7	228	0.047	14.7	434	\
	27/10/2016	0.140	12.1	328	0.286	12.3	648	0.408	9.5	445	1.010	11.7	226	0.121	14.8	532	10
	31/10/2016	0.129	12.1	324	0.169	12.2	617	0.310	8.8	470	0.991	11.7	227	0.072	14.1	478	4
	08/11/2016	0.364	12.3	331	0.326	12.2	568	0.422	8.1	468	1.835	11.6	233	0.241	13.8	544	8
	15/11/2016	0.175	12.3	321	0.092	11.9	573	0.333	8.0	500	1.508	11.5	225	0.221	13.1	475	7
	22/11/2016	0.200	12.2	325	0.097	11.6	566	0.343	8.1	530	1.662	11.5	225	0.228	12.8	470	7
	29/11/2016	0.178	12.1	322	0.070	11.4	587	0.371	7.4	537	1.612	11.4	224	0.210	12.5	464	7
	09/12/2016	0.164	12.1	323	0.050	11.2	572	0.392	6.9	539	1.750	11.4	222	0.189	12.3	478	10
	14/12/2016	0.148	12.0	325	0.038	11.0	532	0.628	7.2	525	1.760	11.4	220	0.176	12.1	474	5
	22/12/2016	0.157	12.0	314	0.097	10.6	528	0.526	6.0	543	1.737	11.4	214	0.195	11.9	509	8
	30/12/2016	0.149	11.9	326	0.063	10.4	529	0.353	4.7	540	1.615	11.2	221	0.152	11.4	470	8
Fall average		0.176	12.1	325	0.127	11.6	579	0.444	7.6	502	1.490	11.5	224	0.168	13.0	484	
Winter	10/01/2017	0.130	11.5	321	0.042	9.8	508	0.427	4.3	528	1.458	11.1	219	0.130	10.8	466	11
	17/01/2017	0.121	11.4	319	0.031	9.4	498	0.410	4.5	500	1.372	11.1	216	0.120	10.5	464	7
	31/01/2017	0.111	11.4	304	0.020	9.2	468	0.405	5.1	480	1.229	11.1	207	0.112	10.1	443	14
	07/02/2017	0.380	11.5	324	1.054	8.5	480	3.720	5.1	435	2.030	11.1	223	0.531	8.7	522	7
	14/02/2017	0.190	11.5	321	0.380	8.9	470	0.913	6.1	478	1.608	11.0	213	0.236	10.1	453	7
	21/02/2017	0.153	11.4	310	0.113	8.7	466	0.843	6.8	489	1.501	11.0	215	0.223	10.2	442	7
	28/02/2017	0.133	11.3	303	0.093	8.8	466	0.750	7.3	472	1.431	11.0	215	0.236	10.4	438	7
	07/03/2017	0.163	11.2	313	0.117	8.8	506	1.080	7.3	499	1.537	10.9	218	0.257	10.3	477	7
	15/03/2017	0.168	11.2	319	0.134	8.8	502	0.793	7.5	505	1.502	10.9	221	0.209	10.7	446	8
	20/03/2017	0.147	11.2	317	0.125	9.0	508	0.653	8.1	504	1.466	11.0	218	0.203	10.8	444	5
	30/03/2017	0.142	11.1	322	0.122	9.0	524	0.832	9.4	509	1.458	10.9	220	0.193	11.5	457	10
Win. average		0.167	11.3	316	0.203	9.0	491	0.984	6.5	491	1.508	11.0	217	0.223	10.4	459	
Spring	06/04/2017	0.130	11.1	321	0.110	9.2	514	0.675	9.8	514	1.431	10.9	219	0.182	11.3	451	7
	11/04/2017	0.124	11.1	318	0.091	9.3	513	0.580	9.8	506	1.374	11.0	216	0.169	11.4	436	5
	18/04/2017	0.119	11.1	317	0.080	9.9	509	0.488	9.9	509	1.337	11.0	215	0.152	11.6	437	7
	28/04/2017	0.116	10.9	316	0.070	9.6	507	0.368	9.4	498	1.256	10.9	215	0.136	11.8	438	10
	08/05/2017	0.199	11.0	322	0.188	10.2	518	0.686	10.4	515	1.417	11.0	218	0.180	12.0	455	10
	12/05/2017	0.155	11.0	322	0.099	10.4	510	0.612	10.6	511	1.357	11.0	216	0.141	12.1	448	4
	19/05/2017	0.120	11.1	320	0.054	10.3	504	0.450	12.0	495	1.301	11.1	216	0.125	12.4	438	7
	26/05/2017	0.096	11.1	318	0.030	10.4	501	0.305	13.5	480	1.251	11.1	215	0.110	12.8	430	7
	31/05/2017	0.085	11.3	318	0.020	10.8	498	0.213	14.6	465	1.199	11.1	214	0.104	13.0	425	5
	12/06/2017	0.071	11.3	320	0.011	11.6	488	0.100	17.8	444	1.162	11.1	212	0.091	13.5	433	12
	26/06/2017	0.058	11.3	321	0.008	12.2	476	0.056	16.6	428	1.109	11.2	209	0.088	14.0	444	14
	30/06/2017	0.160	11.4	327	0.143	12.5	520	0.383	17.0	448	1.801	11.2	223	0.118	14.4	450	4
Spr. average		0.119	11.1	320	0.075	10.5	505	0.410	12.6	484	1.333	11.1	216	0.133	12.5	440	
Summer	07/07/2017	0.118	11.4	325	0.068	12.8	505	0.051	17.5	421	1.376	11.3	215	0.096	14.8	443	7
	15/07/2017	0.126	11.6	325	0.077	12.8	508	0.090	17.8	422	1.421	11.3	218	0.080	15.0	440	8
	23/07/2017	0.114	11.6	328	0.039	12.8	500	0.056	18.7	419	1.367	11.4	215	0.067	15.3	436	8
	25/07/2017	0.138	11.8	334	0.051	12.9	509	0.210	17.9	440	1.475	11.4	216	0.077	15.7	433	2
	10/08/2017	0.060	12.1	332	0.023	13.2	506	0.100	18.5	434	1.319	11.5	215	0.067	16.0	442	16
	07/09/2017	0.044	12.1	326	0.013	12.8	519	0.031	17.6	424	1.155	11.5	216	0.056	16.3	438	28
Sum. average		0.100	11.8	328	0.045	12.9	508	0.090	18.0	427	1.352	11.4	216	0.074	15.5	439	
Average		0.146	11.6	321	0.121	10.7	522	0.535	10.3	483	1.428	11.2	218	0.160	12.5	458	

Table S2 – Discharge (Q), temperature (T) and electrical conductivity (EC) measurements at the springs of Mt. Zirone along the hydrogeologic year 2016-2017 (the Q measures selected for summer recession analysis are highlighted in red).

S2. Hydrographs of the springs of Mt. Prinzera and Mt. Zirone

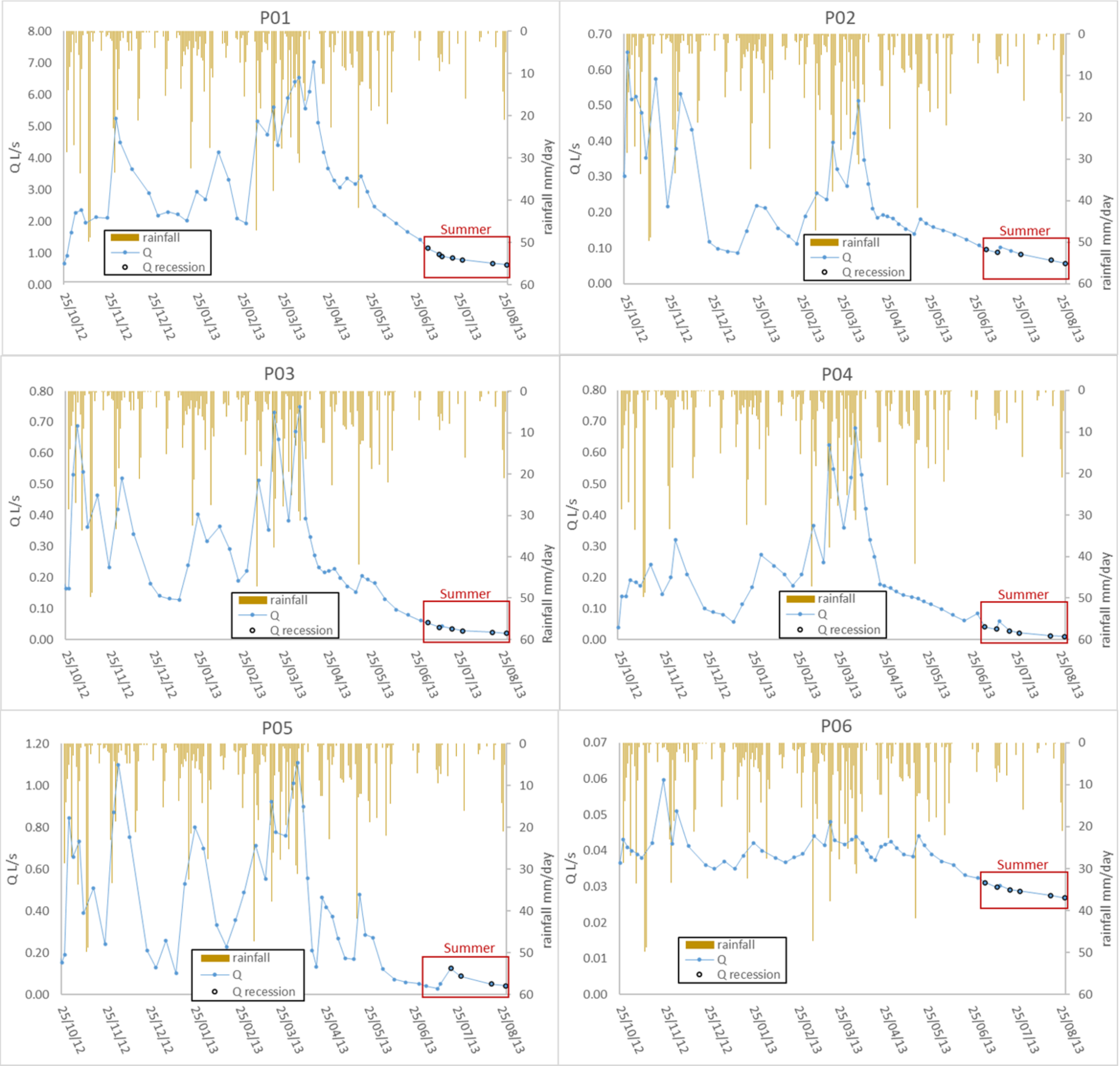

Figure S1 (I)- Hydrographs of the springs of Mt. Prinzera and Mt. Zirone. The summer part the hydrographs analyzed in Fig. 5 of the main article is highlighted in red. The maximum daily rainfall values among the ones registered at the selected monitoring stations (see Section S3 below) are reported on each hydrograph.

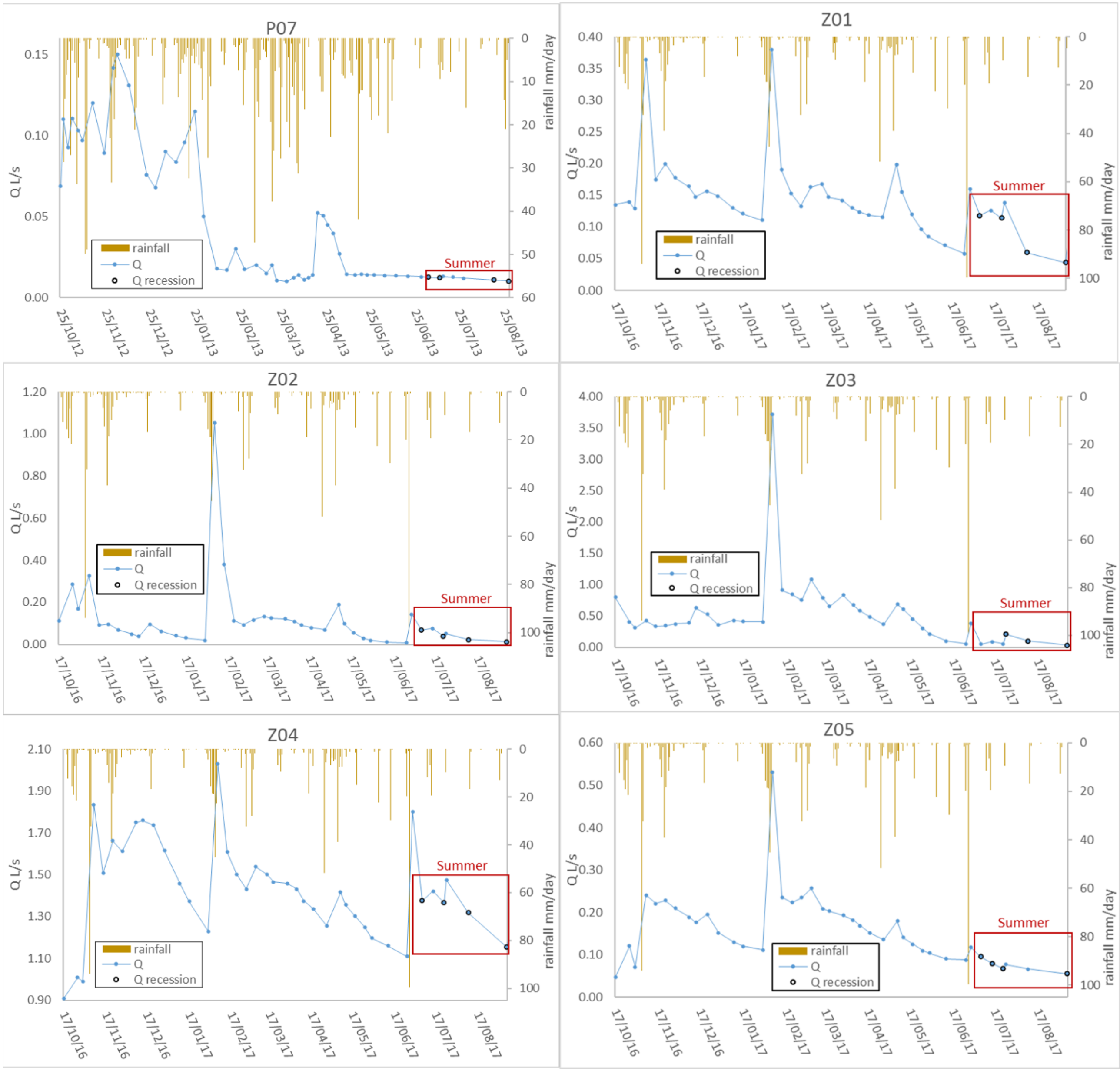

Figure S1 (II)- Hydrographs of the springs of Mt. Prinzera and Mt. Zirone. The summer part the hydrographs analyzed in Fig. 5 of the main article is highlighted in red. The maximum daily rainfall values among the ones registered at the selected monitoring stations (see Section S3 below) are reported on each hydrograph.

S3. Estimation of annual precipitation along hydrogeologic years 2012-2013 (Mt. Prinzera) and 2016-2017 (Mt. Zirone)

Daily precipitation and air temperature data were acquired from several meteorological stations (rain and temperature gauges) of the Hydro-meteorological Service of the Environmental Protection Agency for the Emilia Romagna Region (ARPAE) (Fig. S2).

In order to estimate the annual precipitation P over the catchments of Mt. Prinzera and Mt. Zirone, a linear relationship was identified in the two areas between P and the elevation of selected rain gauges (Fig. S3). Three and four rain gauges were selected for Mt. Prinzera and Mt. Zirone, respectively, among the ones active in the hydrological year of the survey (2012-2013 or 2016-2017). The selected gauges are located at different elevations between 169 and 808 m a.s.l. (Tab. S3).

The areas of Mt. Prinzera and Mt. Zirone were split into four altimetric belts with a 100 m altitude spacing. The rainfall volume corresponding to each belt was determined by multiplying the belt surface for the value of P corresponding to the averaged belt elevation. The sum of P volumes from the different belts was divided by the total area to obtain a value of annual P representative for the whole massif ("P_{TOT}"; Tab. S4).

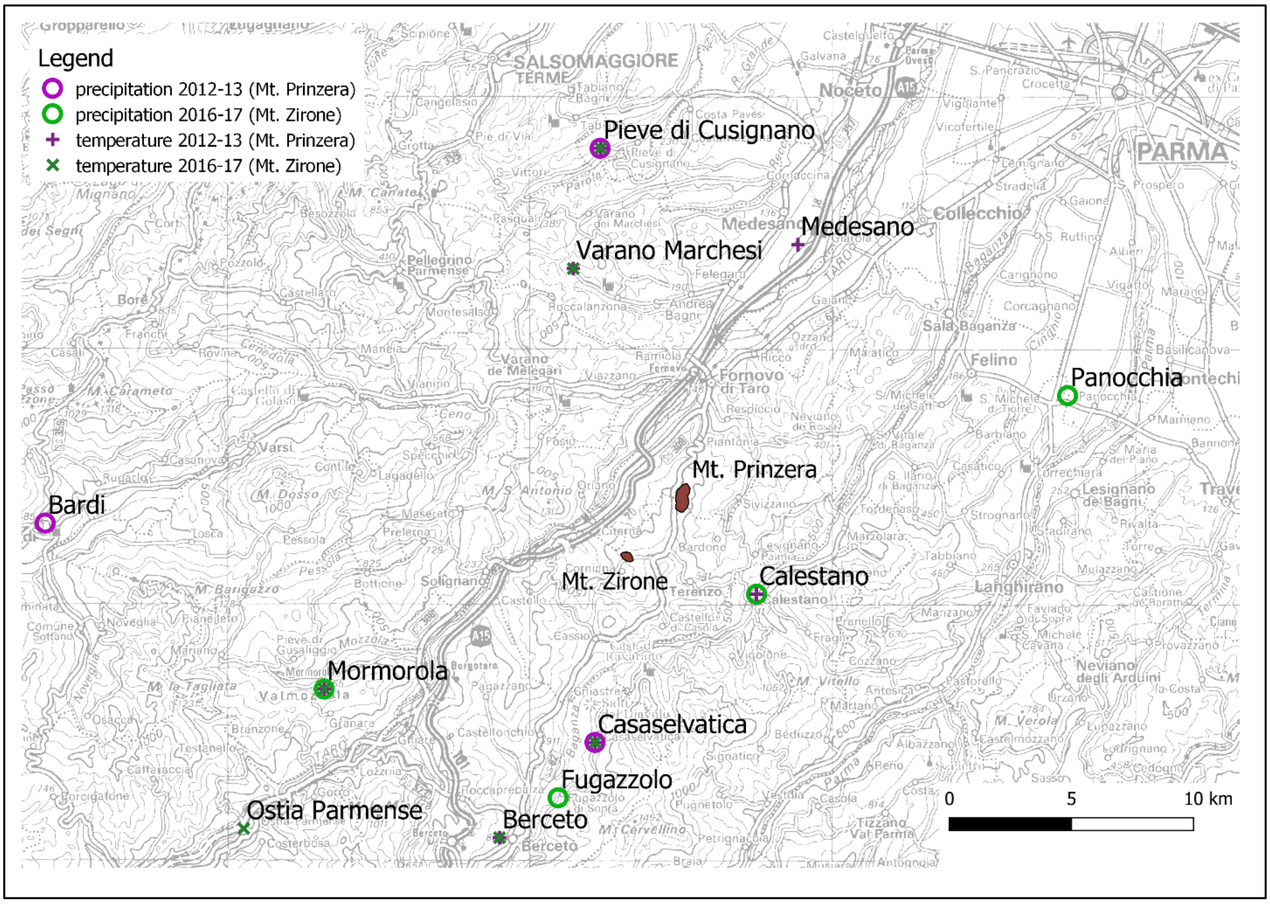

Figure S2 – Location of the meteorological stations selected among the ones active in the hydrogeologic years 2012-2013 and 2016-2017 for daily precipitation and temperature.

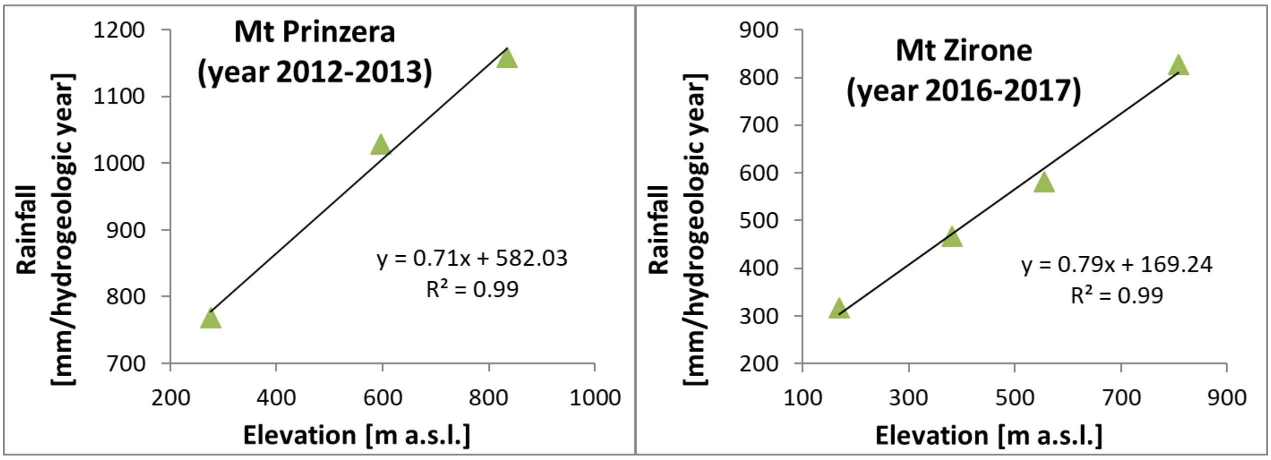

Figure S3 – Linear relationship between the elevation of the meteorological stations and the annual rainfall in the hydrogeologic year of interest.

	Meteorological station (ARPAE)	Elevation	Precipitation [mm]*
Mt. Prinzera	Pieve di Cusignano	277	768
	Bardi	597	1028
	Casaselvatica	834	1159
Mt. Zirone 2016-17	Pannocchia	169	317
	Calestano	381	468
	Mormorola	556	582
	Fugazzolo	808	828

* total precipitation over the monitored hydrologic year

Table S3 – Ground elevation at the selected meteorological stations and annual rainfall during the hydrogeologic year of interest.

	Altimetric belt	Precipitation [mm]	Belt area [m^2]	Precipitation volume [m^3]	P_{TOT} [mm]
Mt. Prinzera 2012-13	A1 (400-500)	900.45	27721.00	24961.37	1010.8
	A2 (500-600)	971.21	324291.00	314954.66	
	A3 (600-700)	1041.97	372578.00	388215.10	
	A4 (700-735)	1102.12	46888.00	51676.02	
Mt. Zirone 2016-17	A1 (400-500)	525.82	32000.00	16826.24	631.94
	A2 (500-600)	605.06	290000.00	175467.40	
	A3 (600-700)	684.30	210000.00	143703.00	
	A4 (700-707)	729.47	2000.00	1458.93	

Table S4 – Altimetric belt areas and estimation of R_{TOT} for Mt. Prinzera and Mt. Zirone. Calculations are described in Section 3.3 of the main text.

S4. Hydrograph analysis by means of “recession plots”

A well-known hydrological method to examine recession hydrographs of streams is to plot the rate of change in discharge (dQ/dt) versus the mean discharge over the dt interval (Q). This kind of plot is also known as “recession plot”. The method was first proposed by Brutsaert and Nieber (1977) to avoid picking the exact time at which recession begins, and further investigated e.g. by Mendoza et al. (2003), Shaw and Riha (2012), Troch et al. (2013).

The recession plot method has been here applied to the spring hydrographs of Mt. Prinzera and Mt. Zirone as an alternative to the Maillet model for the analysis of recession.

We built a recession plot for each spring considering the whole depletion hydrograph, i.e. from the maximum peak of discharge (April and February in the cases in Mt. Prinzera and Mt. Zirone, respectively) down to the end of the hydrologic recession (end of August in both aquifers) (Fig. S4). We removed secondary discharge peaks along the falling limb of the hydrograph by taking into account only decreasing discharge values (i.e. negative values of dQ/dt). The correlation coefficient of the individual recession plots is much higher for the Mt. Prinzera springs (R^2 of 0.71 on average) compared to Mt. Zirone springs (R^2 of 0.54 on average).

The averaged value of the slopes (S) of the recession plots is 2.0 for the springs of both aquifers, consistently with the values obtained by Shaw and Riha (2012) that analyzed individual recession events in streams.

A subdivision in “recession classes” is proposed in the main text that is based on the value of the recession coefficient α of Maillet. The value of S of each spring was chosen as the parameter to be compared with the α of the same spring to assess if the subdivision in recession classes proposed in the main text was maintained when analyzing spring hydrographs with the recession plot method instead of the Maillet model. The comparison between α and S is shown and discussed in the main text.

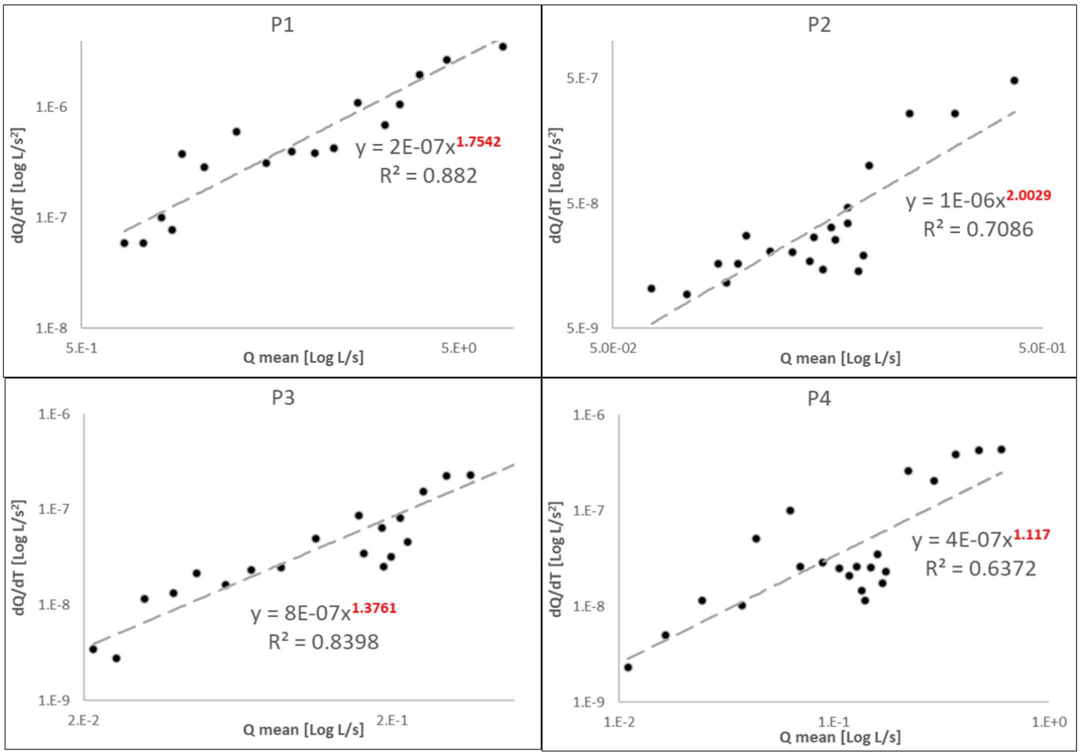

Figure S4 (I) – Recession plots from the depletion hydrographs of the springs of Mt. Prinzera and Mt. Zirone. The value of S is highlighted in red.

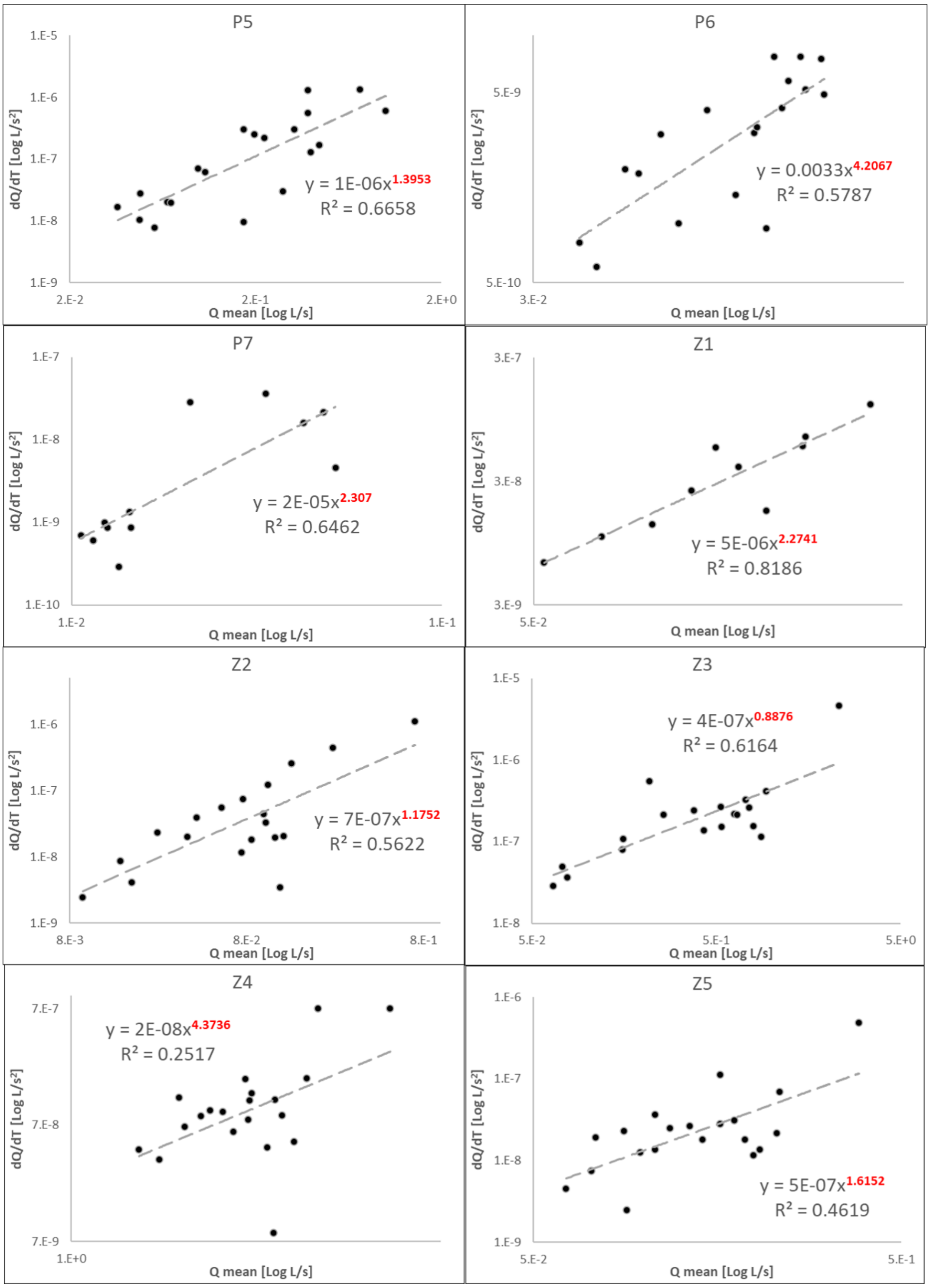

Figure S4 (II) – Recession plots from the depletion hydrographs of the springs of Mt. Prinzera and Mt. Zirone. The value of S is highlighted in red.

S5. Estimation of recharge at Mt. Prinzera and Mt. Zirone from annual water budgeting

The aquifer recharge R_{wb} of Mt. Prinzera and Mt. Zirone was estimated through a water budget equation (S1) for the two monitored years (2012-2013 and 2016-2017, respectively):

(S1) $R_{wb} = (P_{TOT} - ET) \times CPI$

where CPI is the Coefficient of Potential Infiltration that accounts for loss of recharge due to runoff and other minor processes (Civita, 2005) and ET is the annual evapotranspiration estimated using the Turc equation (Turc, 1951) (S2):

(S2) $ET = P_{TOT} / \sqrt{(0.9 + P_{TOT}^2/L^2)}$

where L is a “thermal indicator” that depends on mean annual air temperature (T) and is defined by (S3)

(S3) $L = 300 + 25 \times T + 0.05 \times T^3$

In order to estimate T over the catchments of Mt. Prinzera and Mt. Zirone, a linear relationship was identified in the two areas between the mean annual air T at a meteorological station and the elevation of the station (Fig. S5). Seven and six stations were selected for Mt. Prinzera and Mt. Zirone, respectively, among the ones active in the hydrological year of the survey (2012-13 or 2016-2017) (Fig. S2). The selected stations are located at different elevations between 104 and 834 m a.s.l. (Tab. S5). A mean annual air temperature was assigned to each altimetric belt (Tab. S6). The mean annual air T for the entire catchment was estimated as the average of mean annual temperatures assigned to each belt weighted on the belt areas (“averaged air T” in Tab. S6).

ET was estimated equal to 543 and 486 mm at Mt. Prinzera and Mt. Zirone, respectively, corresponding to the 54 and 77% of P_{TOT}.

Typical ranges of CPI are suggested by (Civita (2005)) for different lithologies. In the case of Mt. Prinzera, a CPI in the mid range of fissured plutonites (25%) allowed estimating a R_{wb} of 117 mm that fits well the R estimated in the main text (see Fig. S6). At Mt. Zirone, a much higher CPI (87%) had to be considered to obtain a good fit between R_{wb} and R, with R_{wb} of 127 mm. Such high value of the coefficient is uncommonly observed for the investigated lithologies. However, several reasons are discussed in the next Section 6 that would justify a much higher infiltration potential at Mt. Zirone compared to Mt. Prinzera.

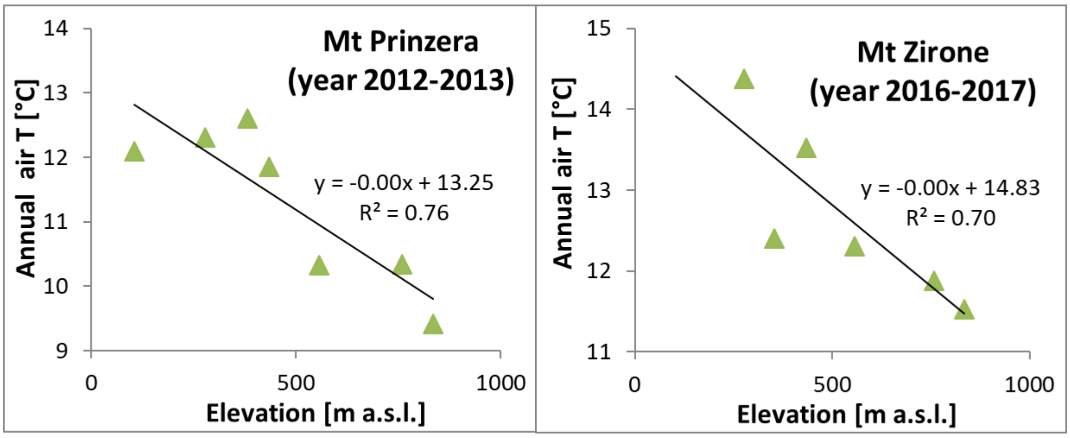

Figure S5 – Linear relationship between the elevation of the meteorological stations and the mean annual air temperature in the hydrogeologic year of interest.

	Meteorological station (ARPAE)	Elevation	T [°C]
Mt. Prinzera 2012-13	Pieve di Cusignano	277	12.30887
	Varano Marchesi	434	11.84751
	Mormorola	556	10.33055
	Berceto	758	10.3336
	Calestano	381	12.59756
	Medesano	104	12.09259
	Casaselvatica	834	9.409191
Mt. Zirone 2016-17	Pieve di Cusignano	277	14.37936
	Ostia Parmense	354	12.40505
	Varano Marchesi	434	13.52554
	Mormorola	556	12.3085
	Berceto	758	11.88294
	Casaselvatica	834	11.52532

* mean annual air temperature at the gauge

Table S5 – Ground elevation at the selected meteorological stations and mean annual air temperature during the hydrogeologic year of interest.

	Altimetric belt	annual air T [°C]	Belt area [m^2]	averaged air T [°C]
Mt. Prinzera 2012-13	A1 (400-500)	11.41	27721.00	10.76
	A2 (500-600)	11.00	324291.00	
	A3 (600-700)	10.59	372578.00	
	A4 (700-735)	10.18	46888.00	
Mt. Zirone 2016-17	A1 (400-500)	13.03	32000.00	12.49
	A2 (500-600)	12.63	290000.00	
	A3 (600-700)	12.23	210000.00	
	A4 (700-707)	11.83	2000.00	

Table S6 – Estimation of averaged air T at Mt. Prinzera and Mt. Zirone as the average of the mean annual temperature at different elevations weighted on belt areas of the same elevation.

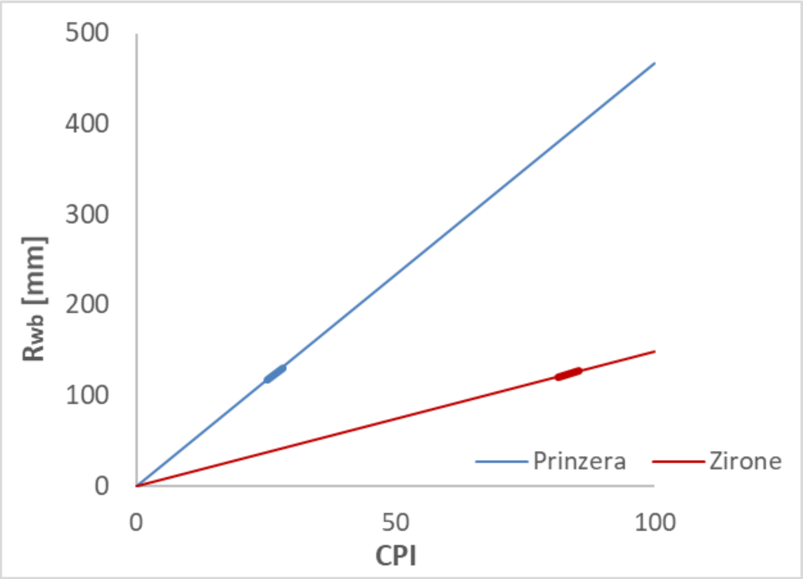

Figure S6 – R_{wb} variation at varying CPI. The thicker segments identify the R values estimated in the main text.

S6. Surface evidences for the infiltration potential at Mt Prinzera and Mt. Zirone

Filed observations on surface morphology, Quaternary cover and fracturing were conducted at Mt. Prinzera and Mt. Zirone providing insights into the infiltration potential of the two aquifers.

The surface of Mt. Zirone is interested by a large number of rock slope deformations (sensu Hungr et al., 2014) likely set on the preexisting tectonic structures (Fig. S7). Such generalized stress-release condition is expected to enhance infiltration of recharging water from the topographic surface into the aquifer. Infiltration is likely exacerbated due to the low thickness of the aquifer (up to 150 m, which is half the maximum thickness of Mt Prinzera aquifer). In contrast, the olistolithe of Mt. Prinzera appears rather intact, with only two rock slope deformations in its northernmost and southernmost edges (Fig. S7). The different degrees of structural relaxation characterizing the two areas are also well discernible in the field, where the fractures at Mt. Zirone appear much wider than that of Mt. Prinzera (Fig. S8). The above observations suggest a lower infiltration potential at Mt Prinzera compared to Mt Zirone.

Preliminary structural surveys were performed at Mt. Prinzera and Mt. Zirone in summer 2014 and 2015, respectively, along two 20 m long scan lines. Whereas the total number of fractures along the scan line was similar in the two cases (1961 at Mt. Prinzera and 2443 at Mt. Zirone), the aperture and persistence of fractures was much lower at Mt. Prinzera, corroborating the hypothesis of higher infiltration potential and overall higher permeability at Mt. Zirone (Fig. S9).

The Quaternary covers in the areas of Mt. Prinzera and Mt. Zirone were analyzed during a field survey from March 2011 to October 2011, using the Technical Regional Map as a base map (1:5000), integrated with aerial photographs (Tab. S7). The results allowed refining the available geological map (Di Dio et al., 2005) based on CARG (Italian Geological Cartography Project) data. The Quaternary deposits consist of eluvial and colluvial deposit, residual cover, active and dormant landslide and mass movements. The woodland cover mostly consists of scattered oak trees and juniper shrubs (Corticelli et al., 2011). The areas not intersected by woodland or Quaternary covers were classified as bedrock outcrop and assumed as the areas contributing most actively to groundwater recharge due to easier recharge infiltration. The overall lower percent of bedrock outcrop over the total aquifer surface at Mt. Prinzera (60%) compared to Mt. Zirone (69%), may contribute to the hypothesized higher infiltration at Mt. Zirone.

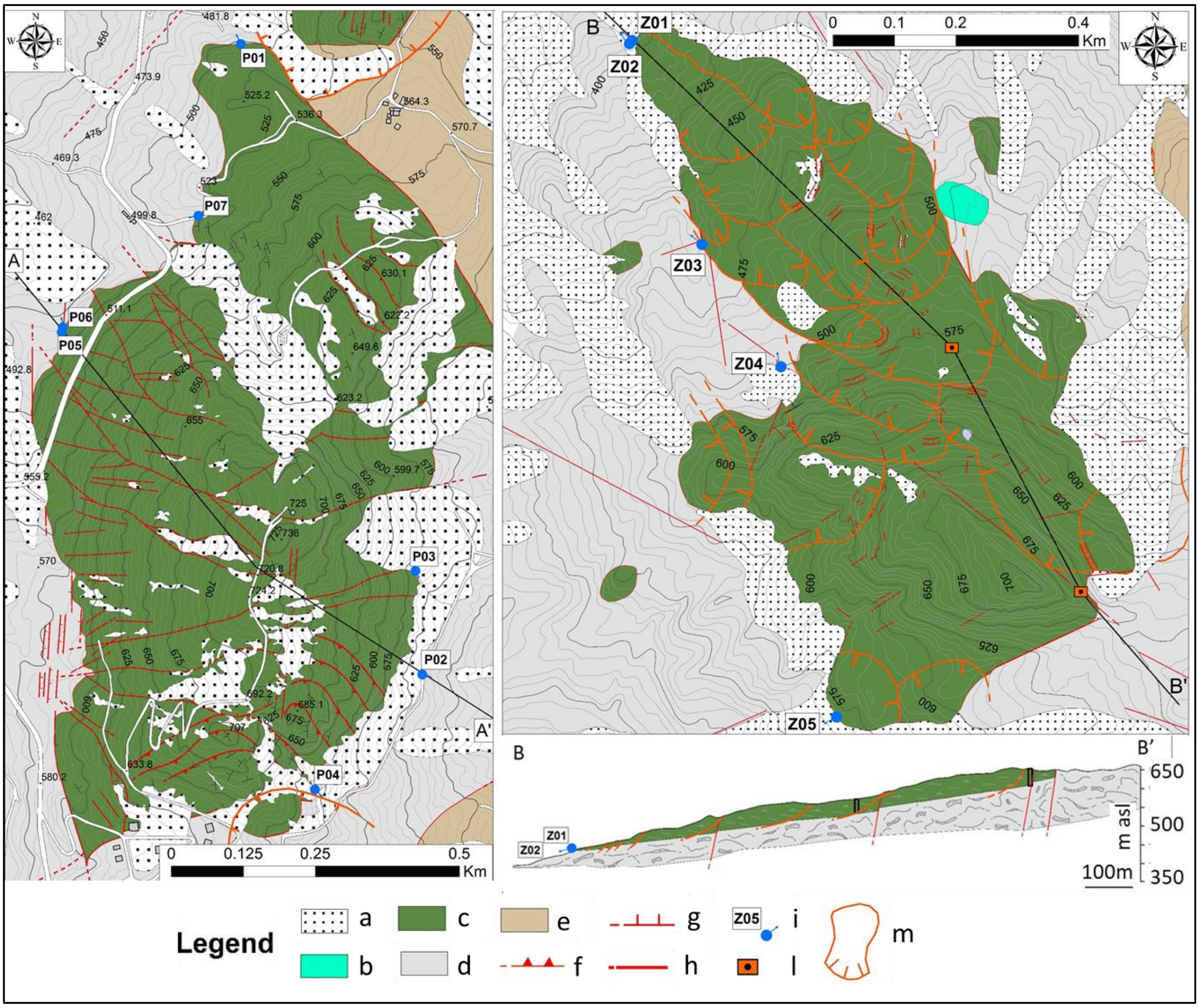

Figure S7 - Geological sketch maps of Mt. Prinzera (left) and Mt. Zirone (right) a: Quaternary deposits; b: Calpionella limestones; c: ophiolite hard-rock aquifers; d: polygenic breccias in clay matrix (aquitard); e: Helminthoid flysch; f: thrust; g: fault (the teeth indicates the downwards moved side); h: tectonic contact; i: perennial spring; l: borehole; m: rock slope deformation boundary (the teeth indicates the downwards moved side).

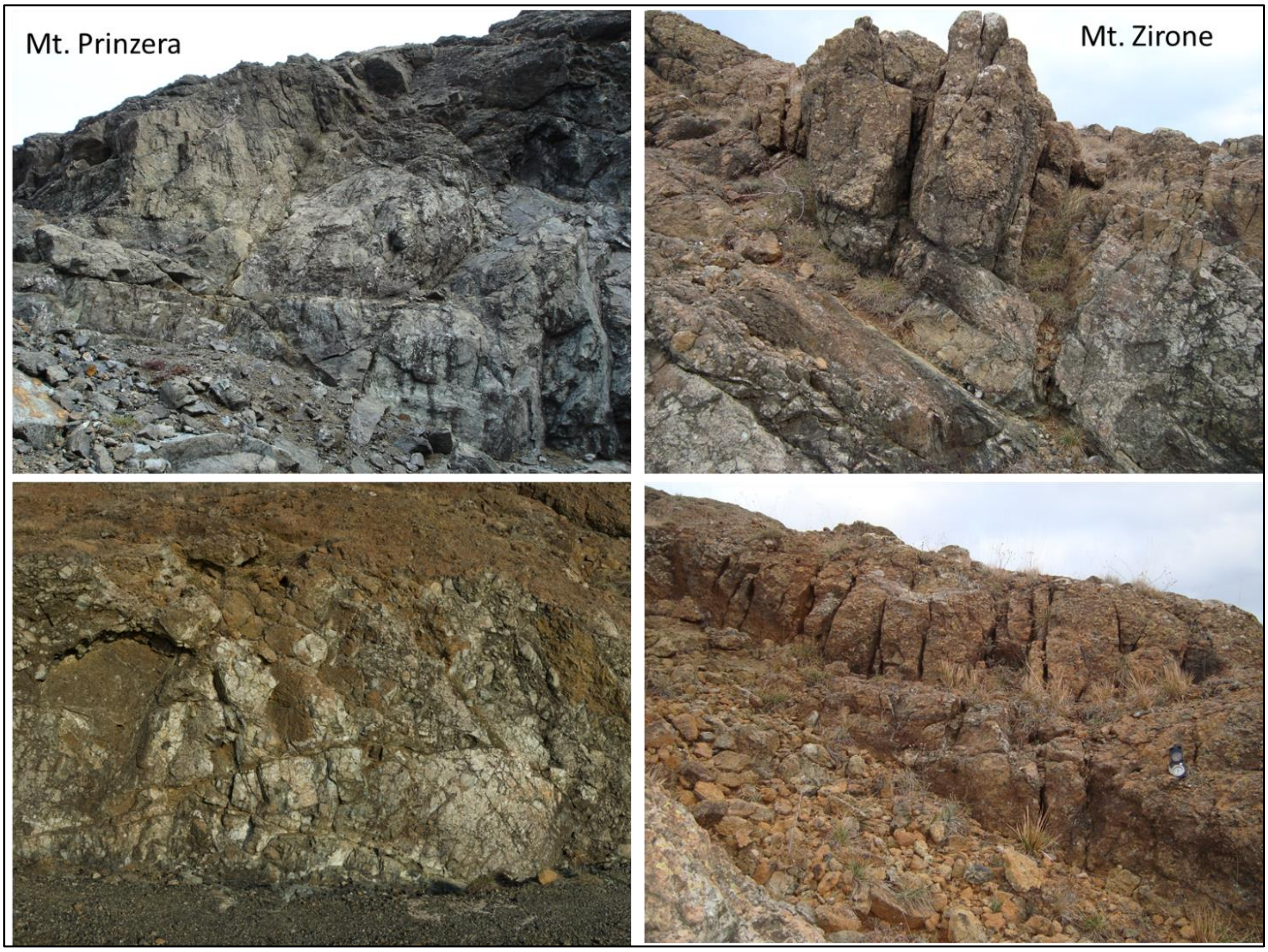

Figure S8 – Pictures from Mt. Prinzera (left) and Mt. Zirone (right) highlighting different stress-release conditions.

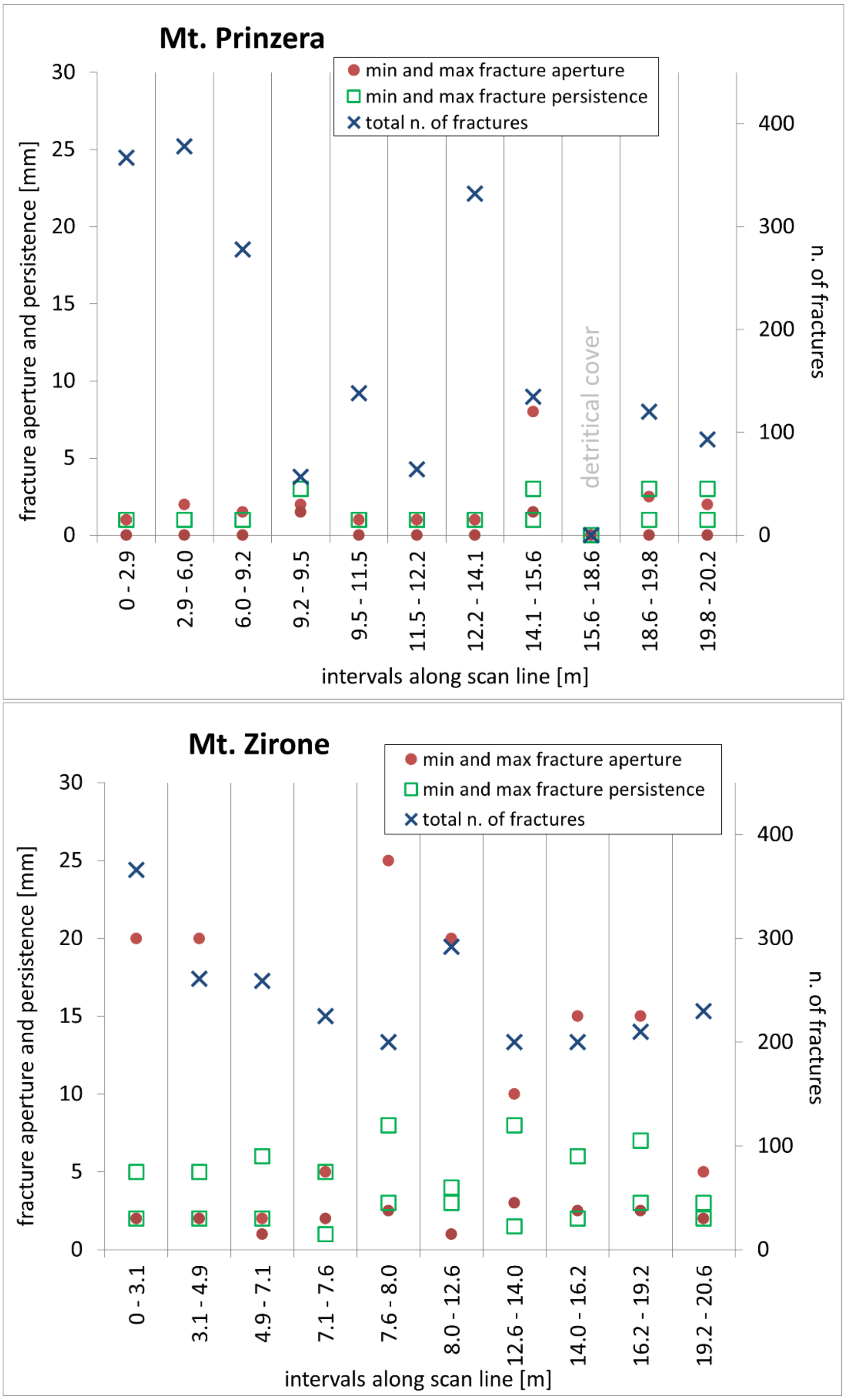

Figure S9 – Results of a preliminary structural survey along 20 m long scan lines at Mt. Prinzera and Mt. Zirone.

			% of total area		% of covered area	
	Mt. Prinzera	**Mt. Zirone**	**Mt. Prinzera**	**Mt. Zirone**	**Mt. Prinzera**	**Mt. Zirone**
Aquifer area (m^2)	771478	534000				
Bed rock outcrop or scattered trees (m^2)	462427	367726	59.94	68.86		
Total cover (m^2)	309051	166274	40.06	31.14		
Quaternary deposit cover (m^2)	148691	25730	19.27	4.82	48.11	15.47
Woodland cover (m^2)	160360	140544	20.79	26.32	51.89	84.53

Table S7- Woodland and Quaternary covers and bedrock outcrop at Mt. Prinzera and Mt. Zirone.

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