Supplementary Materials: Monitoring the Seasonal Hydrology of Alpine Wetlands in Response to Snow Cover Dynamics and Summer Climate: A Novel Approach with Sentinel-2

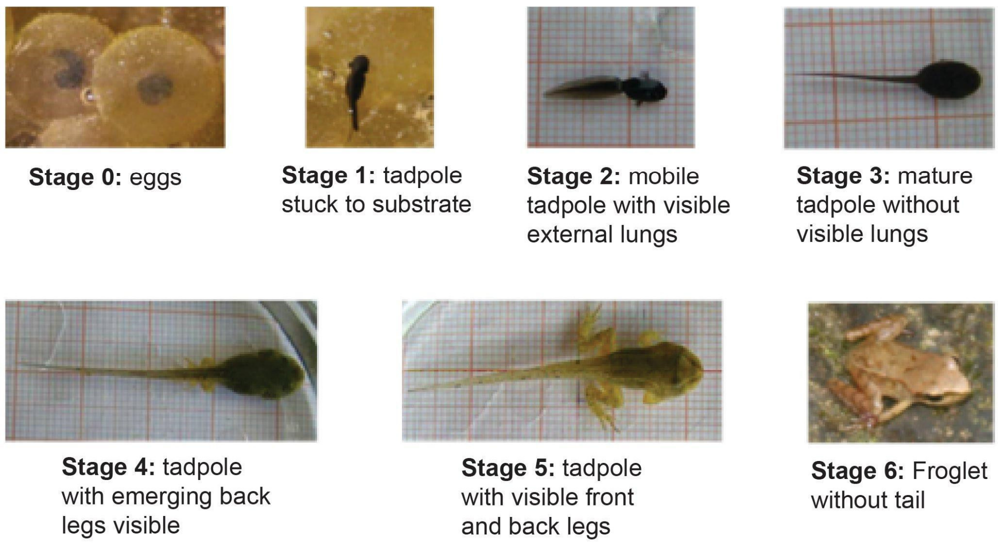

Figure S1. Photos of tadpole development and different phenological stages observed in the field at the Loriaz site (Figure 1D).

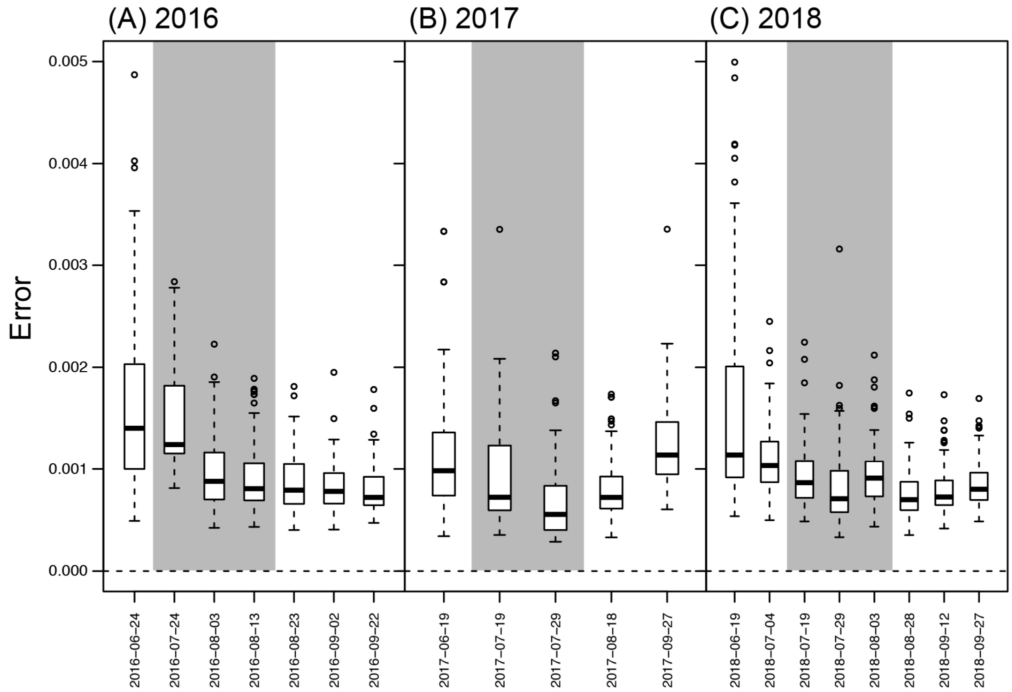

Figure S2. Boxplots of error resulting from linear spectral unmixing for pixels overlapping alpine wetlands for (**A**) 2016, (**B**) 2017, and (**C**) 2018. Each boxplot represents a Sentinel-2 scene date. Values are the result of the simple extract method (fractional estimates for the pixel overlapping the GPS coordinate) and are shown from May to September for each year. The gray rectangle corresponds to the period used to estimate summer water surface area (July 15 to August 15).

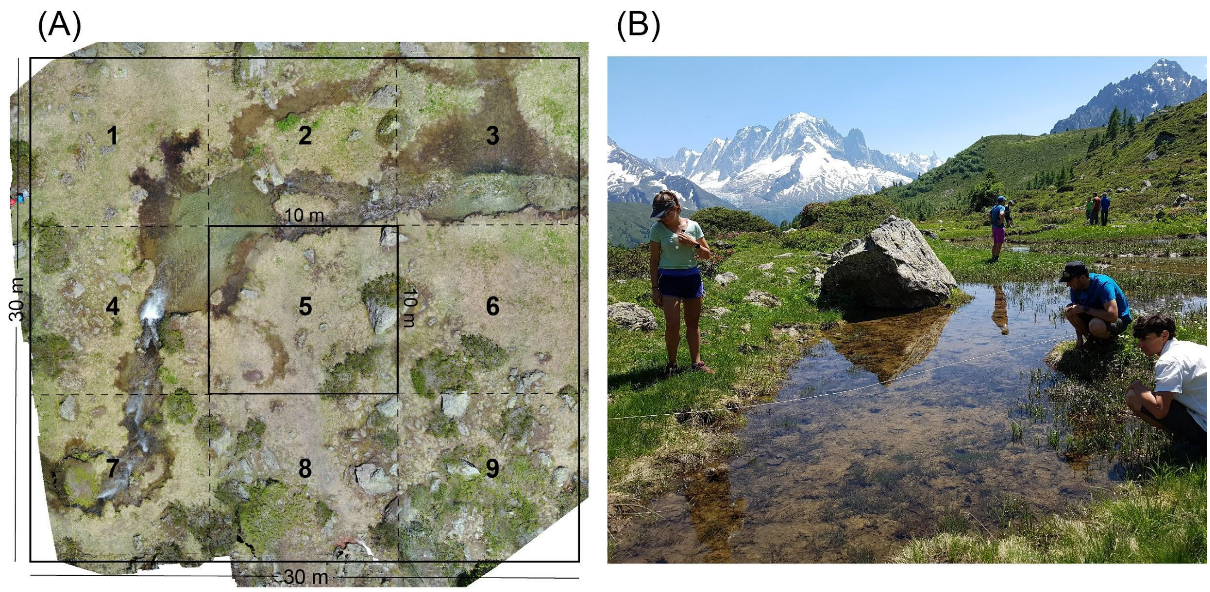

Figure S3. Illustration of the method used to validate Sentinel-2 based estimates of water surface area with respect to ground observations. (**A**) Example 900 m^2 grid centered on a target wetland, composed of nine 10 x 10 m pixels, within which volunteers made visual estimates water surface area on the ground. In order to validate the results of the spectral unmixing algorithm, we extracted water surface area values for the nine Sentinel-2 pixels corresponding with field observations. (**B**) Photo of ground observations underway, using a simple grid constructed using measuring tapes and 30 m lengths of string. For each plot, two groups independently observed the central grid cell (#5 in panel A) in order to quantify observer error.

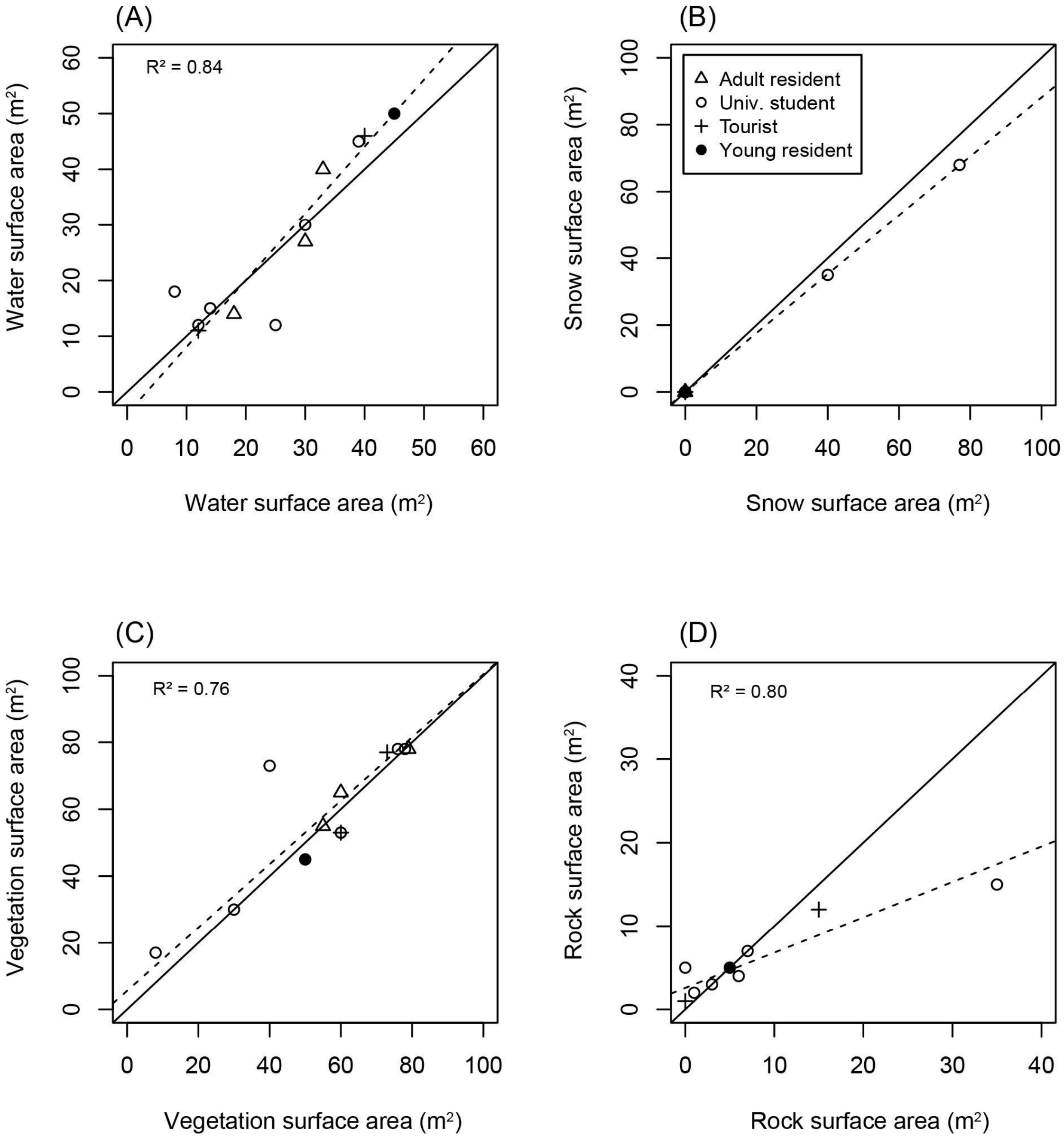

Figure S4. Comparison of visual estimates of the surface area of target endmembers: water, snow, vegetation and rock. Each point represents the same central grid cell (#5, Figure S1) observed independently by two different groups. The solid line represents a 1:1 relationship, while the dashed line represents the line of best fit resulting from linear standardized major axis regression. Point symbols correspond to different observers collecting data during the dates presented in Figure 4.

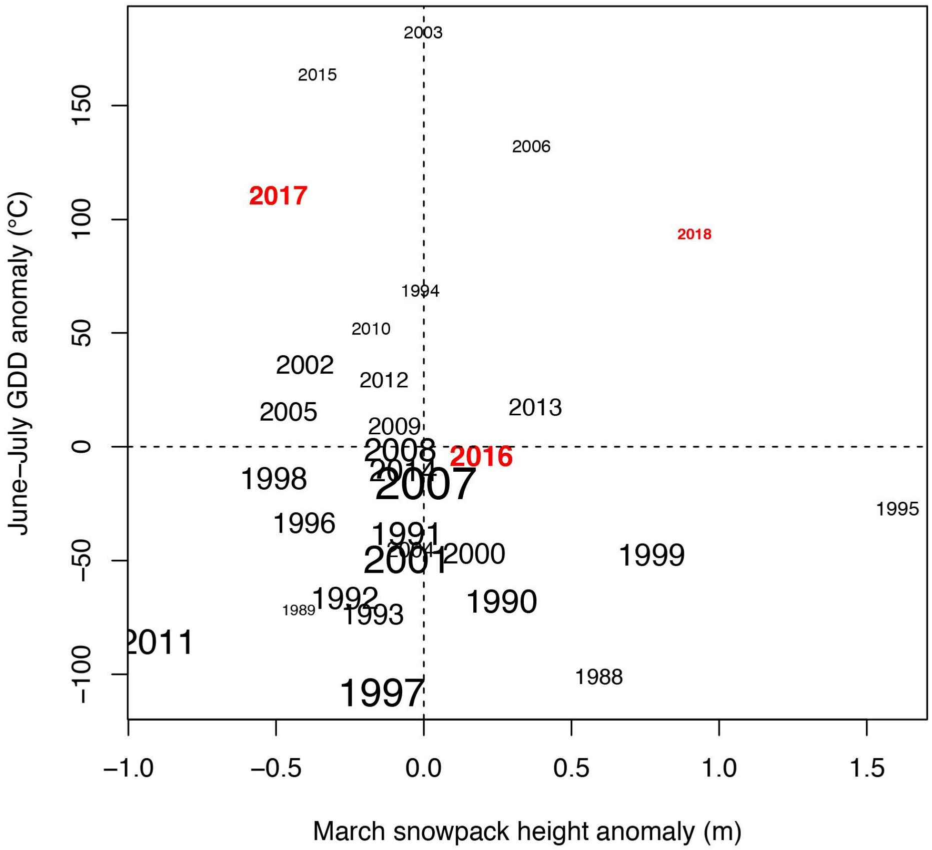

Figure S5. Contextualization of the three study years (2016, 2017, and 2018, shown in red) with respect to 30-year (1988–2018) anomalies of mean March snowpack height and the sum of growing degree days (>0 °C) in June and July. Values were extracted from the SAFRAN-Crocus reanalysis and represent the 1950 to 2250 m a.s.l. elevation band in the Mont-Blanc massif. Text size is proportional to the sum of precipitation in June and July (2016 = + 6 mm, 2017 = − 2.5 mm, 2018 = − 43 mm).

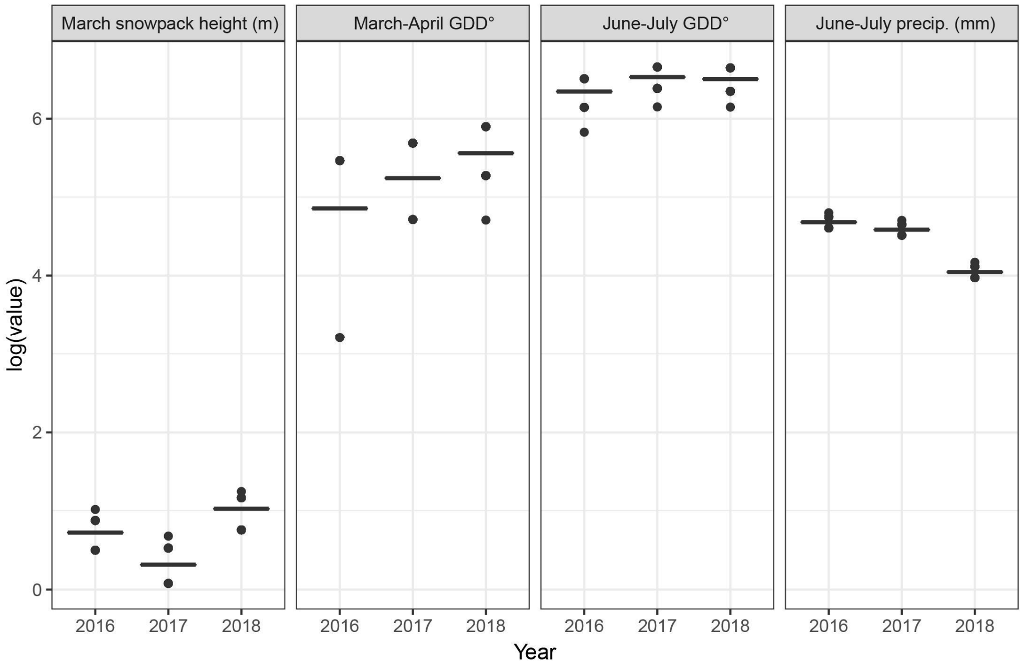

Figure S6. Boxplots of seasonal climate and snowpack variables for 2016, 2017, and 2018 extracted for elevation bands pertaining to studied alpine wetlands in the Mont-Blanc massif (1650–2850 m a.s.l.). Values were normalized using a log function to enable comparison among variables.

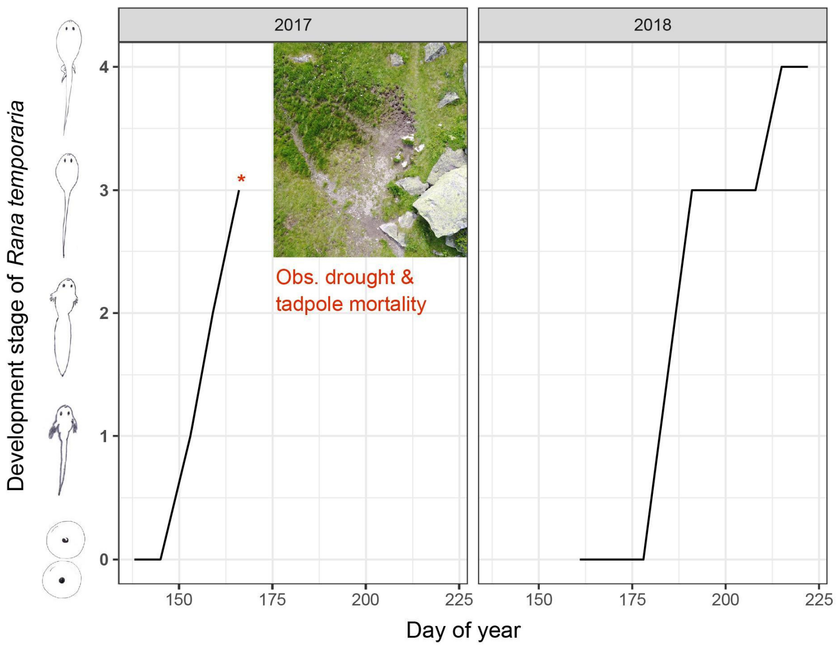

Figure S7. Observed dates of phenological stages of the common frog tadpoles for a survey wetland in 2017 and 2018 (see Figure 1D for location). In July 2017, we observed drought of the wetland associated with mortality of the local tadpole population. Sentinel-2 also estimated zero surface water for this date and location (Figure 4, 7/17/2017).

Response	Predictor	Estimate	Std. Error	P-value		
Summer snowfields	March snowpack depth	0.33	0.07	<0.001	**Model 1A**	
Summer snowfields	June-July GDD	-0.20	0.08	0.008	AIC	16.76
Water surface area	June-July GDD	-0.19	0.08	0.016	X^2 P-val.	0.68
Water surface area	Summer snowfields	0.21	0.08	0.008	R^2 Water SA	0.1
Summer snowfields	March snowpack depth	0.33	0.07	<0.001	**Model 1B**	
Summer snowfields	June-July GDD	-0.20	0.08	0.008	AIC	39.34
Water surface area	June-July GDD	-0.24	0.09	0.008	X^2 P-val.	0
Water surface area	Summer snowfields	0.18	0.08	0.026	R^2 Water SA	0.11
Water surface area	June-July precip.	-0.1	0.09	0.25		
Watershed snowmelt	March snowpack depth	0.47	0.06	<0.001	**Model 2A**	
Watershed snowmelt	April-May GDD	-0.40	0.06	<0.001	AIC	73.88
Water surface area	June-July GDD	-0.26	0.09	0.006	X^2 P-val.	0
Water surface area	Watershed snowmelt	-0.003	0.09	0.976	R^2 Water SA	0.07
Watershed snowmelt	March snowpack depth	0.47	0.06	<0.001	**Model 2B**	
Watershed snowmelt	April-May GDD	-0.40	0.06	<0.001	AIC	163.09
Water surface area	June-July GDD	-0.35	0.10	0.001	X^2 P-val.	0
Water surface area	Watershed snowmelt	-0.04	0.09	0.69	R^2 Water SA	0.09
Water surface area	June-July precip.	-0.16	0.08	0.06		
Wetland snowmelt	March snowpack depth	0.40	0.06	<0.001	**Model 3A**	
Wetland snowmelt	April-May GDD	-0.53	0.06	<0.001	AIC	41.28
Water surface area	June-July GDD	-0.12	0.09	0.18	X^2 P-val.	0
Water surface area	Wetland snowmelt	0.11	0.09	0.25	R^2 Water SA	0.04
Wetland snowmelt	March snowpack depth	0.40	0.06	<0.001	**Model 3B**	
Wetland snowmelt	April-May GDD	-0.53	0.06	<0.001	AIC	67.17
Water surface area	June-July GDD	-0.19	0.20	0.06	X^2 P-val.	0
Water surface area	Wetland snowmelt	-0.09	0.09	0.35	R^2 Water SA	0.05
Water surface area	June-July precip.	-0.12	0.08	0.12		

Table S1. Structural equation model results for all tested models. We retained Model 1A as it was the only statistically acceptable model in line with our initial hypotheses. Models marked with an *A* do not include the sum of precipitation in June and July while models marked *B* do. In terms of annual predictors, we tested three different snowpack parameters in relation to mid-summer water surface area: the percent of watersheds snow covered in July and August (*Summer snowfields*, Model 1), the date at which a watershed dropped below 30% snow cover (*Watershed snowmelt*, Model 2), and local snow melt-out date for wetlands (estimated as the first day with fractional snow cover below 10%, *Wetland snowmelt*, Model 3). We correlated *Summer snowfields* to summer air temperature (June–July GDD), and we correlated *Watershed snowmelt* and *Wetland snowmelt* to spring air temperatures (April–May GDD).