Hydrological characterization of livestock watering ponds in semi-arid rangelands of the southwestern Iberian Peninsula

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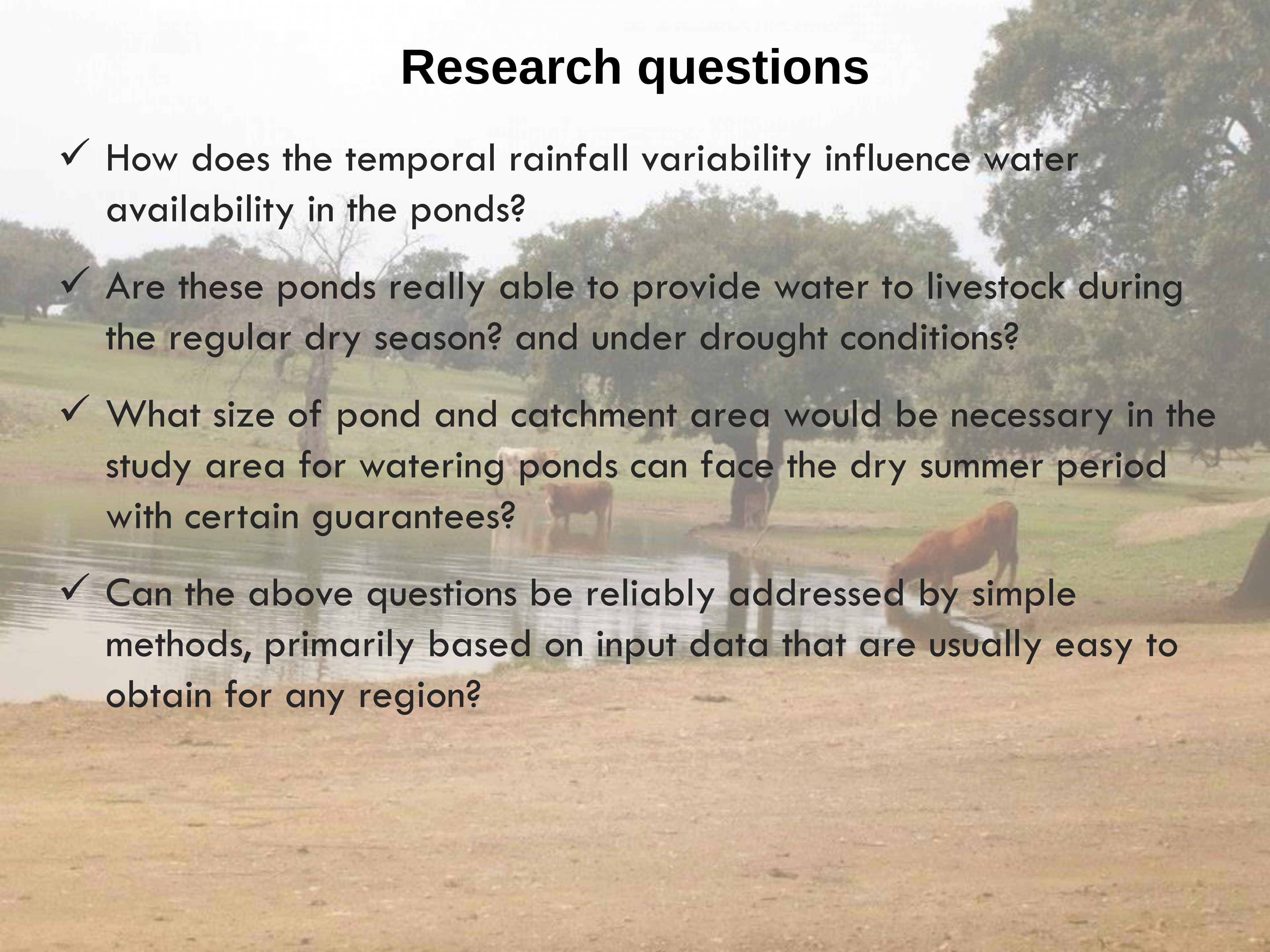
EGU2020-4973
https://doi.org/10.5194/egusphere-egu2020-4973
EGU General Assembly 2020

Motivation

- ✓ Watering ponds are the main source of drinking water supply for livestock in the rangelands of the southwestern Iberian Peninsula. Most of them consist of small earth dams which collect surface runoff of intermittent streams, with pond sizes that rarely exceed 1 ha.
- ✓ Understanding the hydrological functioning of this type of infrastructures is crucial for an efficient water management in extensive livestock farms, especially in semi-arid areas, where water resources are often scarce.
- ✓ In this regard, scientific studies conducted on man-made watering ponds under real operating situations are very scarce, especially in Mediterranean areas. Therefore, there is limited knowledge about the effectiveness of these infrastructures in terms of their capacity for water storage, particularly in the driest years.



Research questions

- ✓ How does the temporal rainfall variability influence water availability in the ponds?
- ✓ Are these ponds really able to provide water to livestock during the regular dry season? and under drought conditions?
- ✓ What size of pond and catchment area would be necessary in the study area for watering ponds can face the dry summer period with certain guarantees?
- ✓ Can the above questions be reliably addressed by simple methods, primarily based on input data that are usually easy to obtain for any region?

Study Area

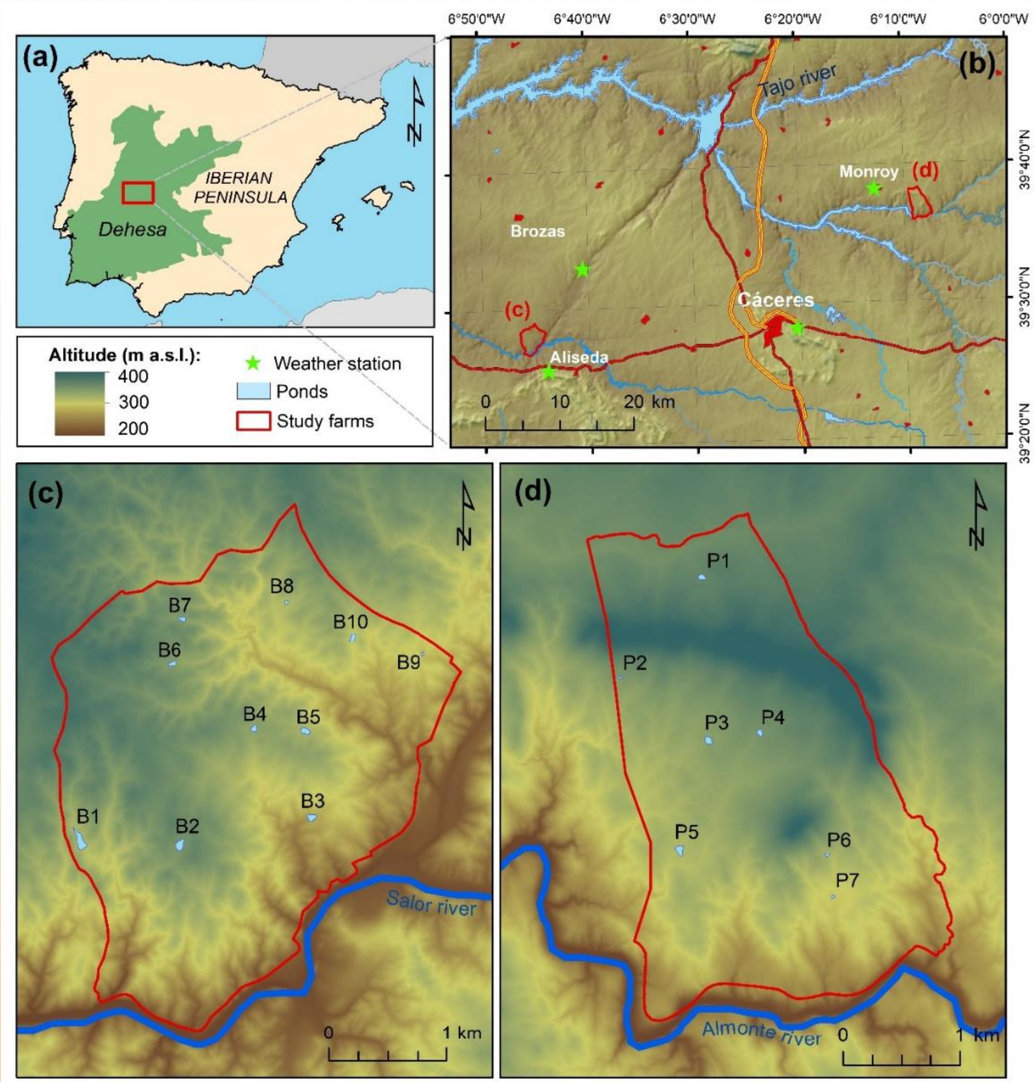


Figure 1: (**a**) Approximate extension of rangelands in the southwestern Iberian Peninsula; (**b**) Location of the study farms and the meteorological stations; (**c, d**) Location of the watering ponds in the study farms.

<u>Characteristics of the study farms</u>

- **Land use system**: Dehesa (grasslands with a disperse tree cover, mainly evergreen oaks Quercus ilex var. rotundifolia). Livestock rearing (sheep, goats, pigs and cows) is the dominant land use.
- **Geomorphology**: gently undulating erosion surfaces, incised by small river channels with periodic discharge, giving rise to increasing slope gradients as approaching major rivers.
- **Dominant bedrocks**: slates and greywacke.
- **Dominant soils**: Leptosols and Cambisols.

<u>Climatology</u>

- Mediterranean climate, with a humid season from October to May and a very pronounced dry and hot season (June–September), particularly in July and August.
- Rainfall shows high temporal variability, both annually and inter-annually.
- Mean annual rainfall: 541 mm (city of Cáceres)
- Mean annual reference evapotranspiration: 1451 mm (city of Cáceres)

Methodology

Baseline data

- ✓ Daily rainfall data for the period 1997-2018, collected from several meteorological stations in the vicinity of the study farms (data provided by the Spanish Agency for Meteorology, AEMET).

- ✓ Aerial photographs of high resolution (orthophotos) of the study farms, available online at the Spanish National Geographic Information Center (CNIG) and Google Earth. A total number of 21 orthophotos were gathered, with flight dates ranging from 2002 to 2018.

  - ➢ In each orthophoto, the flooded area (**A**) for each pond was digitized and quantified.
  - ➢ The limits of the flooded area corresponding to the maximum capacity of each pond ($\mathbf{A_{max}}$) was identified through photointerpretation.
  - ➢ The $\mathbf{A/A_{max}}$ ratio was chosen as a proxy for water availability in the ponds.

- ✓ Digital elevation models (pixel size: 5 m), available online (CNIG), were used to determine the catchment area ($\mathbf{S_c}$) for each pond.

- ✓ Detailed bathymetries of three representative ponds of the study area.

  - ➢ A relation Volume-Area was obtained by fitting a power function to the data derived from these bathymetries, resulting in the following equation (1): $V = 0.0031 x A^{1.793}$ (goodness of fit: $R^2=0.98$; $p<0.001$)
  - ➢ Equation (1) was used to estimate the maximum volumes ($\mathbf{V_{max}}$) of the study ponds from the respective values of A_{max} (the uncertainty due to this approximation was quantified in approximately ±25%).

Methodology

Influence of rainfall variability on water availability in the ponds

✓ For each pond, simple linear regression analyses were carried out between the A/A_{max} ratios observed in the orthophotos and antecedent rainfall, considering accumulation periods (AP's) of antecedent rainfall from 1 to 12 months:

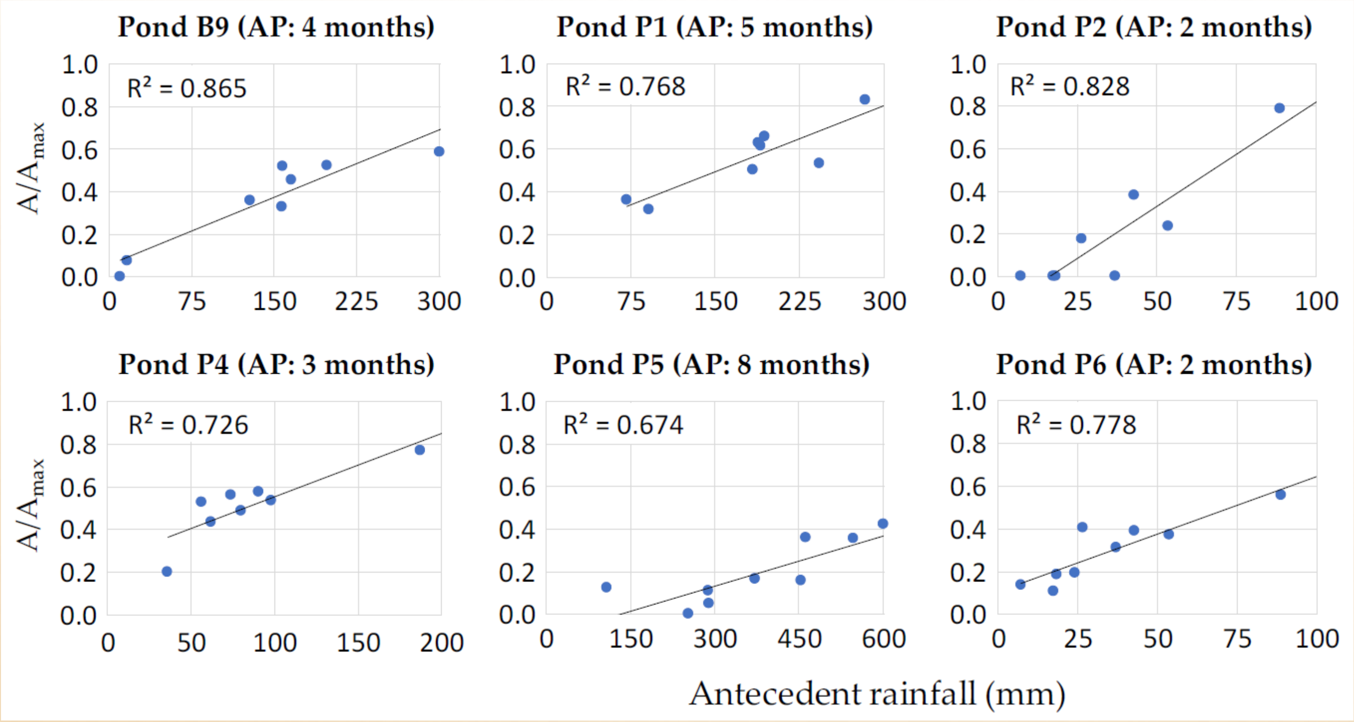


Figure 2: Some examples of the linear regression analyses carried out between A/A_{max} and antecedent rainfall.

For each pond, the variable $\mathbf{RAP_R}$ was defined as the weighted mean value of the AP's (in months) for which significant correlations ($p<0.05$) were obtained, using as weighting factors the values of R^2 obtained for each AP.

Methodology

Hydrological response of ponds to droughts

✓ The monthly values of the Standard Precipitation Index (SPI; McKee et al., 1993*), computed over several timescales (3, 6, 9, and 12 months), were used to identify and characterize drought events in each of the study sites.

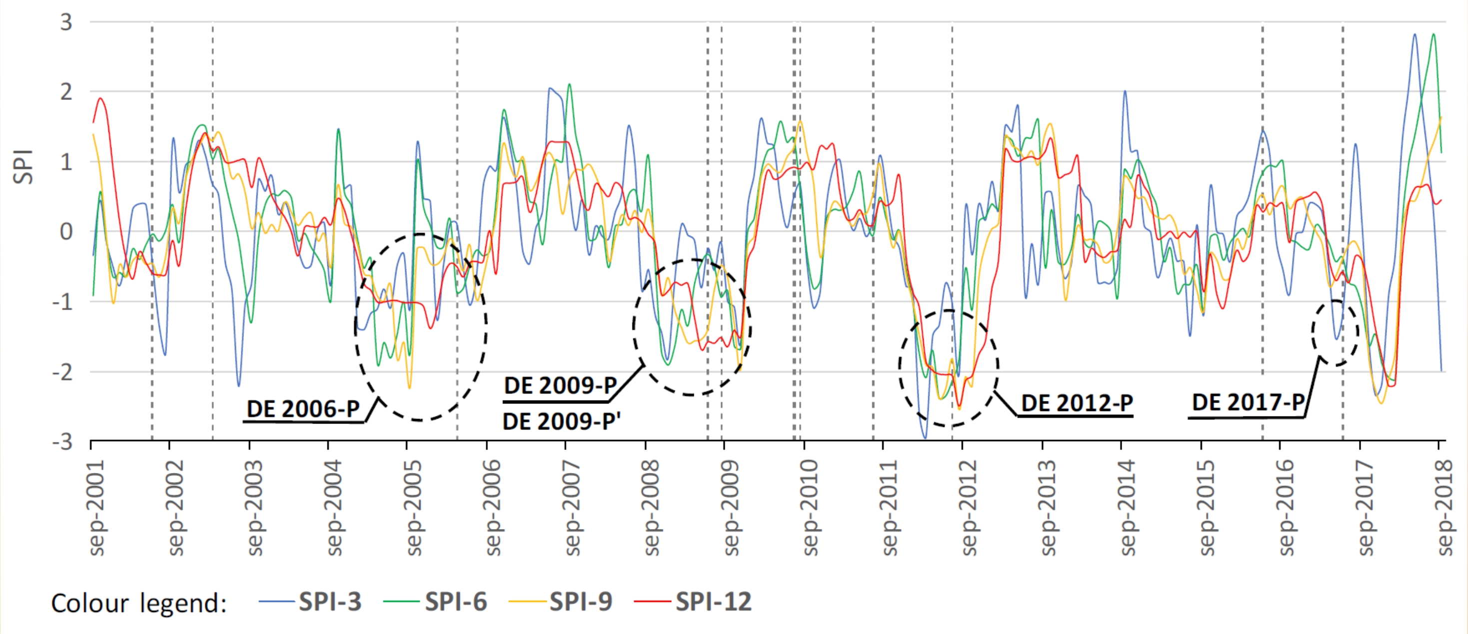


Figure 3: Monthly SPI values obtained for one of the study sites. The vertical pointed lines mark the dates in which the orthophotos used in this study were taken. The drought events (DE) matching such dates are indicated.

* McKee, T.B.; Doesken, N.J.; Kleist, J. The relationship of drought frequency and duration to time scales. In Proceedings of the 8th Conference on Applied Climatology, Anaheim, CA, USA, 17–22 January 1993.

Methodology

Effectiveness of the ponds

- ✓ The reliability of the ponds (**R_{pond}**), defined as the probability of ponds having enough water to meet the demands, was used as a proxy for their effectiveness. The following equation, adapted from the one proposed by Baek and Coles (2011)*, was used to calculate the reliability of each of the study ponds:

$$R_{pond} = (N_T - N_{failure})/N_T$$

- where N_T is the total number of observations of the flooded area (A) made on orthophotos taken during summer dates, and $N_{failure}$ is the number of such observations for which A = 0.

* Baek, C.W.; Coles, N.A. Defining reliability for rainwater harvesting systems. In Proceedings of the 19th International Congress on Modelling and Simulation (Modsim2011), Perth, Australia, 12–16 December 2011.

Results

Influence of rainfall variability on water availability in the ponds (I)

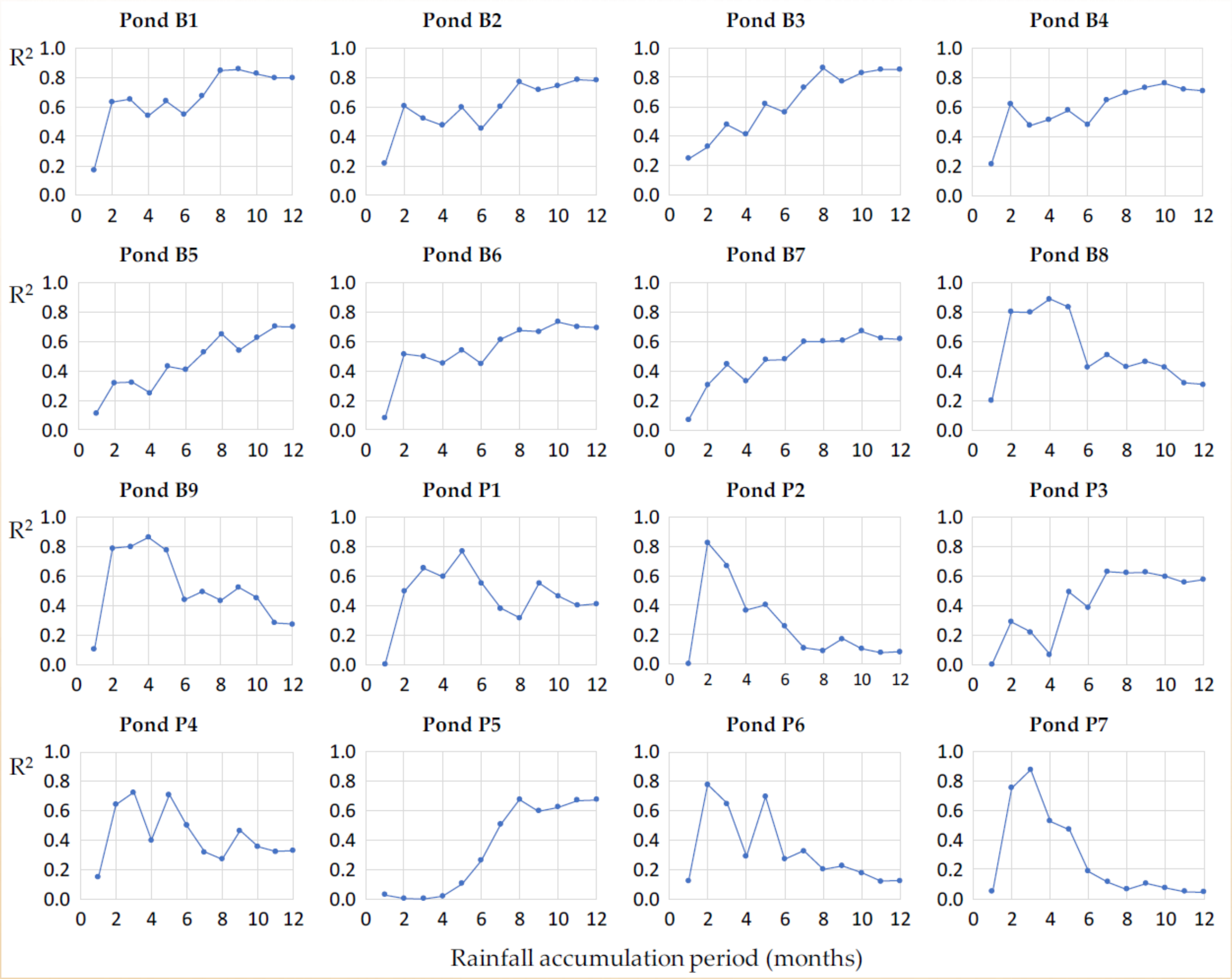


Figure 4: Coefficients of determination (R^2) obtained by linear regression analyses between A/A_{max} and antecedent rainfall, for accumulation periods from 1 to 12 months.

Results

Influence of rainfall variability on water availability in the ponds (II)

Table rows are ordered depending on pond size

Pond	A_{max} (m^2)	R^2 values and significance levels obtained for several accumulation periods of P (in months)											
		1	2	3	4	5	6	7	8	9	10	11	12
P2	304		0.83 **	0.67 *									
P7	468		0.75 **	0.87 ***	0.53 *	0.47 *							
B9	649		0.79 **	0.80 **	0.87 ***	0.78 **				0.52 *			
B8	667		0.80 ***	0.80 ***	0.89 ***	0.83 ***	0.43 *	0.51 *	0.43 *	0.46 *	0.43 *		
P6	770		0.78 **	0.65 **		0.70 **							
P1	1901			0.65 *	0.60 *	0.77 **	0.55 *			0.55 *			
P4	1970		0.64 *	0.73 **		0.71 **	0.50 *						
B7	2030			0.44 *		0.48 *	0.48 *	0.60 **	0.60 **	0.61 **	0.67 **	0.62 **	0.62 **
B6	2198		0.51 *	0.50 *	0.45 *	0.54 *	0.45 *	0.61 *	0.68 **	0.67 **	0.73 **	0.70 **	0.69 **
B4	2390		0.62 **	0.47 *	0.51 *	0.58 *	0.48 *	0.65 **	0.70 **	0.73 **	0.76 **	0.72 **	0.71 **
B3	3067			0.48 *		0.62 *	0.56 *	0.73 **	0.86 ***	0.77 **	0.83 ***	0.85 ***	0.85 ***
P3	3277					0.50 *		0.63 *	0.62 *	0.63 *	0.60 *	0.56 *	0.58 *
B5	3857					0.43 *	0.41 *	0.53 *	0.65 **	0.54 *	0.63 **	0.70 **	0.70 **
P5	3950							0.50 *	0.67 **	0.60 *	0.62 *	0.67 **	0.67 **
B2	4748		0.60 *	0.52 *	0.47 *	0.59 *	0.45 *	0.60 *	0.77 **	0.71 **	0.74 **	0.78 **	0.78 **
B1	7946		0.63 *	0.65 *	0.54 *	0.64 *	0.55 *	0.67 *	0.85 **	0.85 **	0.82 **	0.80 **	0.79 **

Colour legend: $R^2 < 0.6$; $0.6 < R^2 < 0.7$; $0.7 < R^2 < 0.8$; $R^2 > 0.8$

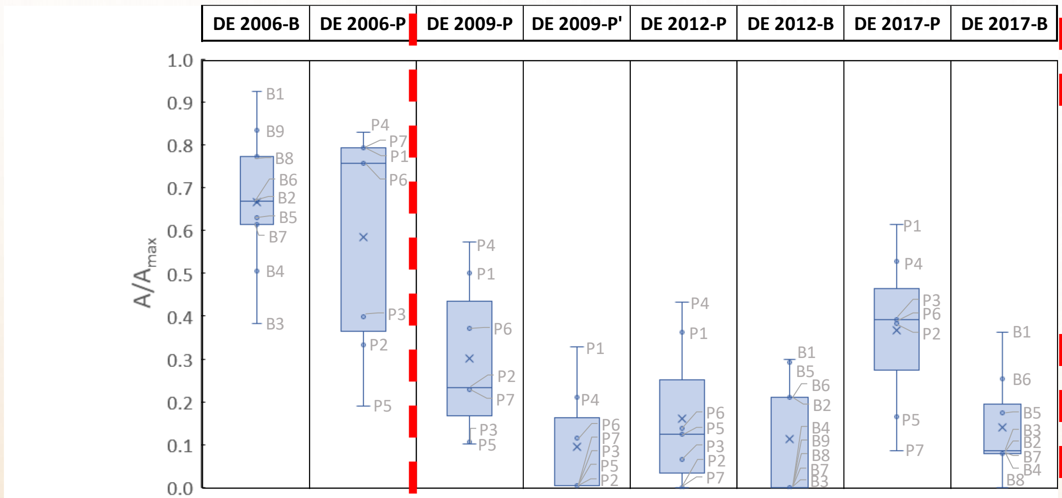
Figure 5: Coefficients of determination (R^2) obtained by linear regression analyses between A/A_{max} and antecedent rainfall, for accumulation periods from 1 to 12 months, and levels of statistical significance: * ($p<0.05$); ** ($p<0.01$); *** ($p<0.001$). Omitted R^2 values correspond to those analyzes that were not significant ($p>0.05$).

Water availability in small ponds was highly influenced by AP between 2 and 5 months, while the hydrological response of large ponds was more strongly determined by AP in excess of 6 months.

Since the dry season in the study area usually lasts for more than 4 months, it is expected that the smallest ponds will reach very low water levels (or dry out) at the end of the summer, regardless of rainfall occurring in the previous months. Instead, large ponds could remain operational throughout the dry season, if it rains enough during the humid season.

Results

Hydrological response of ponds to droughts



Observation date		04/25/2006	04/29/2006	06/17/2009	08/03/2009	07/05/2012	09/03/2012	06/15/2017	07/28/2017
Drought Intensity	SPI-3					-1.04		-1.22	-0.32
	SPI-6			-0.33	-0.94	-2.13	-0.10		
	SPI-9		-0.28	-1.39	-0.48	-1.82	-1.52		-0.42
	SPI-12	-0.32	-0.50	-1.58	-1.52	-2.07	-1.41		-1.07
Drought Magnitude	∑SPI-3					10.15		2.75	2.76
	∑SPI-6			9.28	10.73	13.41	10.62		
	∑SPI-9		7.73	8.57	9.88	12.76	11.32		3.22
	∑SPI-12	17.08	12.26	4.51	7.63	11.10	9.37		3.06

Figure 6: Boxplot of mean (symbol x) and quartiles of the observed A/A$_{max}$ ratios in the study ponds. Each box corresponds to each of the orthophotos that were taken during drought events (DE's). The intensity and magnitude of such DE's, corresponding to the observation dates and computed over several timescales, are also indicated (drought magnitude was calculated through the positive sum of the SPI values for all months from the beginning of the drought event until the observation date). Empty cells indicate that, for the corresponding timescale, no drought event was occurring on the observation date.

These observations correspond to the orthophotos that were taken in summertime while a drought event was occurring.

Regardless of the magnitude and intensity of these drought events, low values of the A/A$_{max}$ ratio were generally observed in the ponds, almost always remaining below 0.4. Taking into account that this value of the A/A$_{max}$ ratio corresponds approximately to a pond filling level (V/V$_{max}$) of 0.2 (according to Equation (1)), these results evidence a high vulnerability of the ponds to drought.

Results

Influence of pond size

With a value of $RAP_R > 7$ months, these ponds should remain operational throughout the dry season, if it rains enough during the humid season.

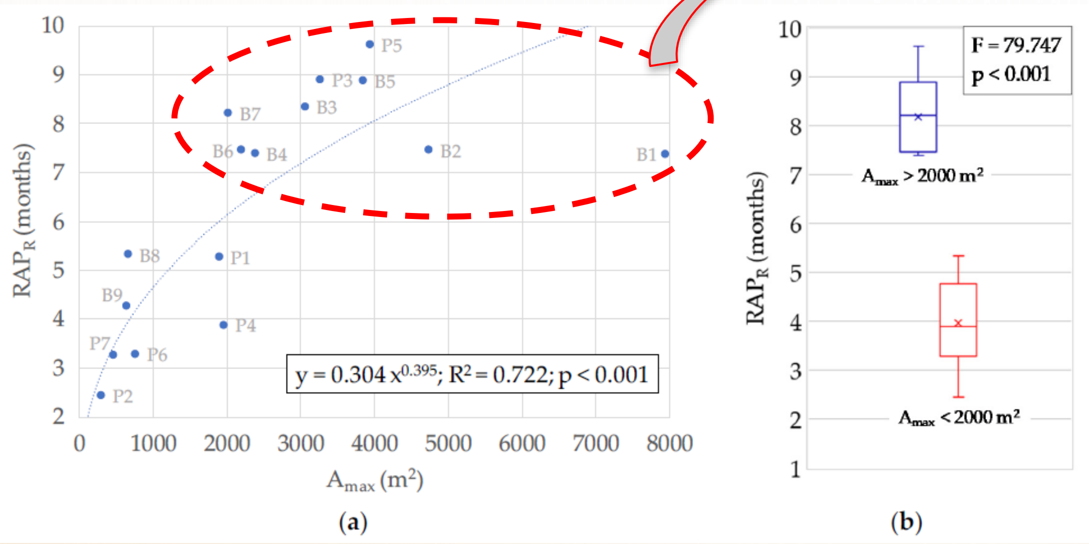


Figure 7: (**a**) Relationship between RAP_R and the size of the ponds (A_{max}); (**b**) Boxplot showing mean (symbol x) and quartiles of RAP_R grouped according A_{max}. The values of F and p of the ANOVA test are also indicated.

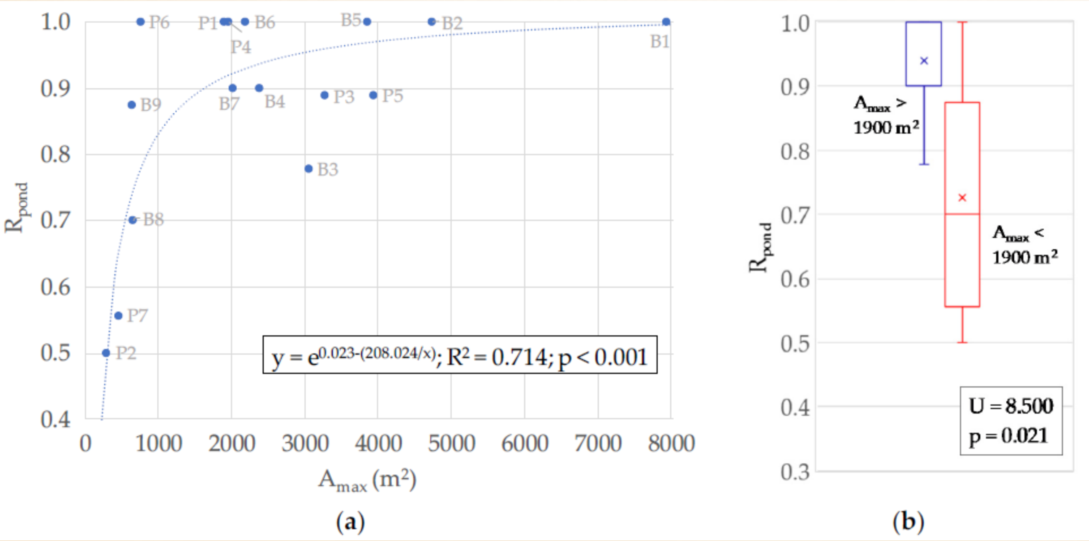


Figure 8: (**a**) Relationship between pond reliability (R_{pond}) and the size of the ponds (A_{max}); (**b**) Boxplot of mean (symbol x) and quartiles of R_{pond} grouped according A_{max}. The values of U and p of the Mann-Whitney test are also indicated.

Results

Influence of catchment area

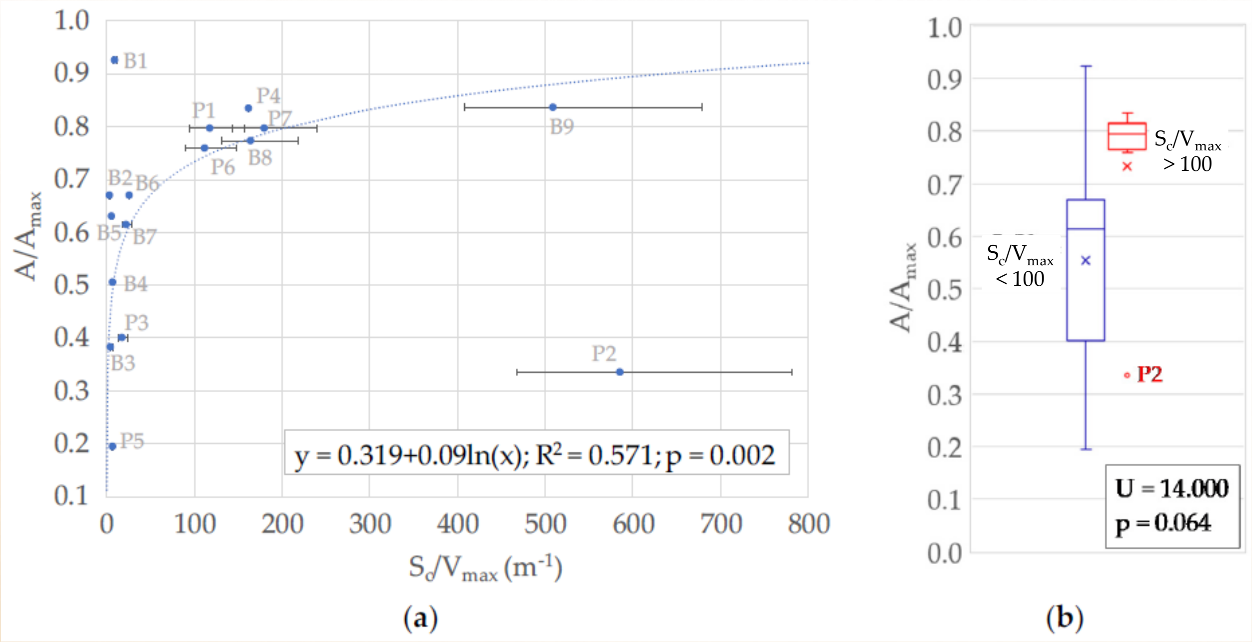


Figure 9: (**a**) Relationship between the observed A/A_{max} ratios in the ponds (from orthophotos of 2006) and the respective values of the S_c/V_{max} ratio. Error bars are included for V_{max} variations of ±25% with respect to the values estimated by Equation (1). The results of the regression analysis are presented in the graph (anomalous values of ponds B1 and P2 were not considered*); (**b**) Boxplot depicting mean values (symbol x), quartiles, and outliers of the A/A_{max} ratios observed for ponds with S_c/V_{max} ratio below and above 100 m^{-1}. The U and p values of the Mann-Whitney test are also shown.

High values of water availability were observed in ponds with S_c/V_{max} ratios in excess of 100 m^{-1} (except for pond P2*). Contrarily, ponds with S_c/V_{max} ratios of less than 50 m^{-1} presented significantly lower filling levels (except for pond B1*).

Excessive uncertainties were obtained in ponds with very high S_c/V_{max} ratios (B9 and P2) but, in general, uncertainty remained in acceptable proportions for the regular values of the S_c/V_{max} ratio and, in any case, it was compatible with the purpose of the analysis.

* The high A/A_{max} ratio observed for pond B1 can be explained by its exceptionally high storage capacity (more than four times higher than the mean of the study ponds), which could allow the pond to accumulate water remaining from previous more rainy years. On the contrary, the small size of pond P2 and the extraordinarily high extension of its catchment in relation to the pond capacity presumably lead to frequent overflows, which would prevent the pond from storing all the runoff produced in the basin.

Conclusions

Influence of rainfall variability on water availability in the ponds

- The high correlations observed between water availability in the ponds and the antecedent rainfall point to precipitation as the main driving factor of the hydrological regime of livestock watering ponds in the study area.
- The accumulation periods of antecedent rainfall that best explained the hydrological response of the ponds depended largely on their size. While water availability in the small ponds (<2000 m^2) was greatly influenced by rainfall accumulation periods between 2 and 5 months, in the large ones (>2000 m^2), the best correlations were obtained for rainfall accumulation periods in excess of 6 months, evidencing that the hydrological behavior of the latter was influenced by rainfall that occurred during the whole humid season.

Influence of pond size and catchment area

- The size of the ponds and the catchment area have proven to be key factors in the effectiveness of the watering ponds. Our findings point to a minimum pond area of 2000 m^2 and a catchment area/storage capacity ratio around 100 m^{-1} in order for watering ponds can face the dry summer period with certain guarantees, at least in regular hydrological years.

Hydrological response of ponds to droughts

- Under drought conditions, the majority of the ponds presented critical levels of water availability, evidencing a high vulnerability to droughts. In view of these results, it is clear that relying exclusively on watering ponds as water supply system on farms would pose a risk.

Thanks for your attention

Acknowledgments:

This work has been financially supported by the Research Project IB16052 “Desarrollo de un Sistema de evaluación integral espacialmente distribuido para explotaciones de ganadería extensiva” funded by Junta de Extremadura (Regional Government of Extremadura) and the European Fund of Regional Development (European Union).

The authors would like to give especial thanks to Manuel Sánchez Fernández, Álvaro Gómez Gutiérrez, and Alberto Alfonso Torreño for helping us with the field work.