Robustness to droughts in a multi-level governance irrigation system: A statistical analysis of *Riegos del Alto Aragon* irrigation systems

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Abstract

The chapter examines successful drought management by testing hypotheses derived from the theory of the commons. Utilizing a series of OLS models, the paper compares the performance of 38 systems in a large irrigation system in Spain during and after a severe drought. According to the results, leadership, monitoring and flexible property rights have a positive effect on drought performance while group size and collective choice do not. The effect of leadership and property rights is mediated by rules at higher governance levels, pointing to the importance of taking into account multi-level dynamics when studying social-ecological phenomena. Interactions between the independent variables are also explored with regard to additional qualitative data and theory to understand other important dynamics. Overall, the results show the relevance of using and adapting the theory of the commons to understand sustainability issues other than those embodied in overexploitation issues. The distinction between different appropriation situations as well as the observance of multi-level and other interactions seems a promising research path in that regard.

INTRODUCTION

Extreme water scarcity events can be associated to ecological phenomena (such as increase or decrease in rainfall patterns), social phenomena (i.e. overexploitation of hydrological resources) or both. Theory regarding sustainable management of natural resources has long focused on the latter phenomena (Gordon 1954, Hardin 1968, Ostrom 1990, Agrawal 2001, Poteete et al. 2010, Janssen et al. 2004, Schoon 2008, Cox and Ross 2011). Whether existing theory can help explain the robustness of management systems to ecological disturbances, like droughts, is an open question, and an increasingly relevant one. There is evidence that permanent rainfall changes are taking place at global and regional scales and that those changes will result in droughts and floods, among other natural phenomena (Allan 2001, Overpeck et al. 2010).

This research aims to add to the understanding of the conditions that enhance robustness to droughts by studying the performance of a large set of irrigation associations located in the “Riegos del Alto Aragon” (RAA) irrigation project, in north-eastern Spain. The question that drives this research is: which biophysical and institutional features contribute to the performance of the irrigation associations during drought periods?

Much of current theory on natural resources governance is based on the study of irrigation systems and management. An important body of theory emerging from the study of irrigation is the theory of the commons (Ostrom 1992, Ostrom et al. 1994, Cox et al. 2010). The theory explains the ability of natural resource users to overcome overexploitation threats as mediated by the creation and maintenance of common property regimes. A more recent body of literature that also builds on evidence from irrigation systems are the theories of social-ecological robustness (Lam 2006, Anderies et al. 2006, Costeja 2009, Cox 2009). The theory aims to explain the ability of governance and ecological systems to overcome disturbances to the functional interactions that link one to the other. This study aims to contribute to both theoretical strands by testing hypotheses derived from the theory of the commons in the context of a disturbance.

While droughts in the RAA project and Spain are not a new phenomenon, their management still constitutes a challenge due to their increasing unpredictability, recurrence and severity (CHE 2007). In the last four decades there has been a decreasing rainfall trend and an increasing evapotranspiration trend (López-Moreno et al. 2010, Vicente-Serrano et al., 2010), and it is estimated that average river gauge in the area decreases by around 10 percent in 2025 (CHE 2007).

This research uses one of the most severe droughts that Spain has gone through in the last century as a natural experiment in assessing the robustness of the irrigation systems within the RAA project. The assessment is based on a pre-post-test design and combines statistical analysis with more qualitative analysis.

The paper is structured in 7 sections. The two first sections introduce the empirical and theoretical background of the study. The third section presents the methodology. The fifth and sixth sections illustrate and discuss the results. And the seventh section summarizes the findings and contributions of the study.

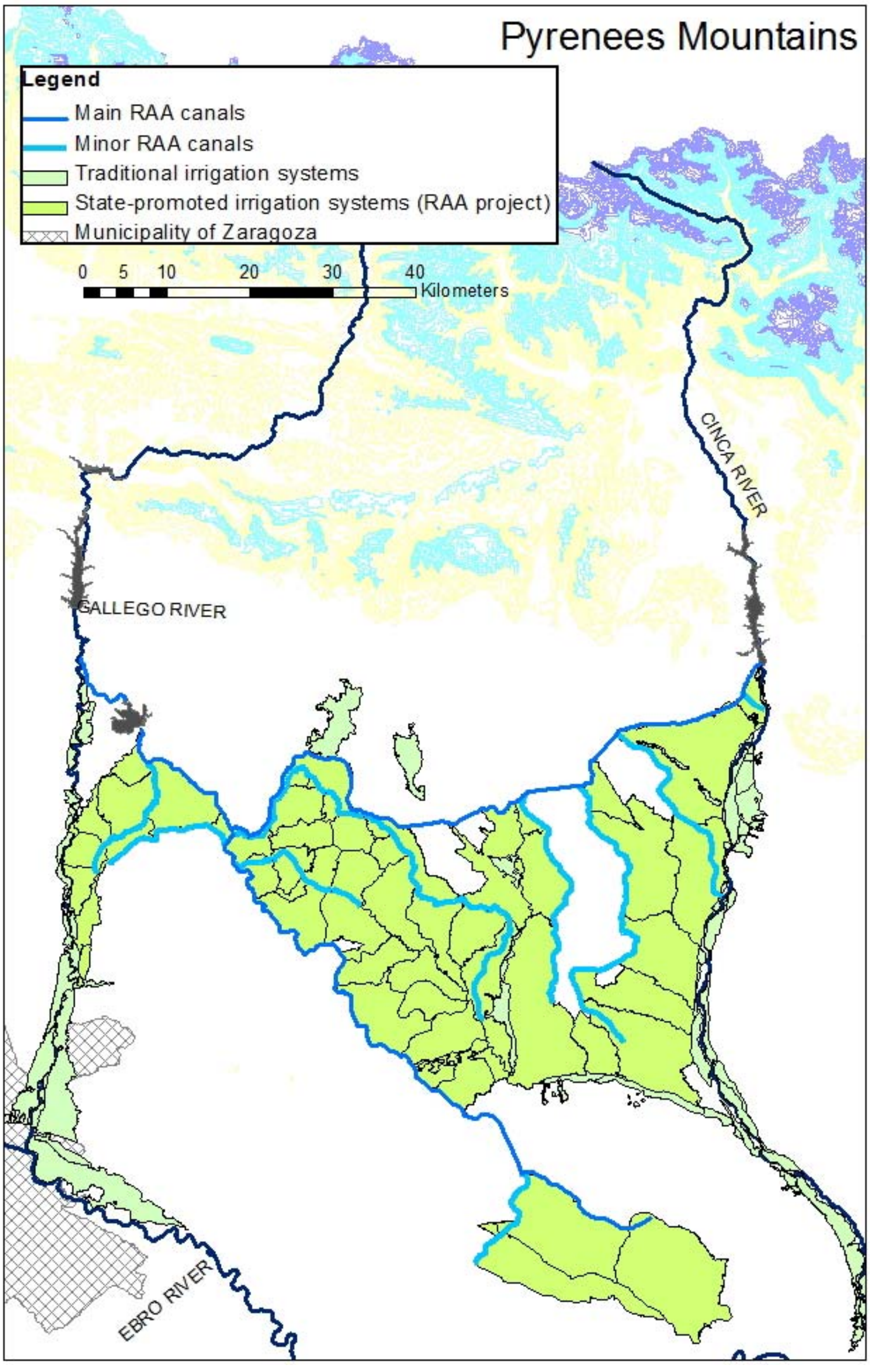
BACKGROUND

Ecological and institutional background of the RAA project

The RAA project is one of the oldest and largest state promoted irrigation projects in the country. It was launched by the Spanish government in the first half of the 20th Century and currently encompasses 50 irrigation communities for a total of approximately 126,000 irrigable hectares (see Fig. 1).

The local climate is semi-arid Mediterranean continental, with a mean annual temperature of 14.5 C, and an annual precipitation around 350mm (13.8 inch) (Vicente-Serrano & Cuadrats-Prats 2007). The Pyrenees mountain range, which is located at the North of the system, supplies most of the available water through snowmelt.

Figure 1. Map of the RAA irrigation project



Source: Data obtained from GCRAA and Regional Government of Aragon

The RAA project relies on a series of reservoirs located in the Gallego and Cinca basins for a total storage capacity of around 930Hm^3. Water from the reservoirs is delivered to the irrigation systems via a network of 223km of main and minor canals. The system also counts on a network of more than 2,000km of drainage canals.

Two geomorphologic units can be distinguished in the RAA project. The first corresponds to platforms of relatively low slope. Most common soil types in the platforms are Xerosol Gypsic and Xerosol Calcic, which tend to have low available water holding capacity (AWHC) and high infiltration (Playan et al. 2000). Because of their low slope and good drainage these soils can be highly productive, but only if enough water is available. The second geomorphologic unit corresponds to slopes and alluvial terraces located at lower altitudes. Soils in terraces can be classified as Fluvisol Eutric, which have high AWHC but poor drainage (Playan et al. 2000). Thus, these soils can perform better than platform soils during periods of water scarcity.

The relatively high proportion of platforms in the RAA area makes soil permeability a salient feature of the RAA hydraulic system**.** Soil permeability permits water seepage and reutilization given the appropriate drainage infrastructure. The drainage system of the RAA project enables to collect and reuse much of the water that percolates from upstream irrigation.

Finally, more than 90 percent of the land in the RAA project produces one crop per season (Lecina et al. 2010). There are two main classes of crops that farmers can grow: winter and summer crops. Summer crops like alfalfa or corn cannot be grown without appropriate irrigation in the area, while winter crops like wheat or barley are a bit less dependent on irrigation. This is mainly due to two reasons. First summer crops present higher water requirements than winter crops; water need coefficients are generally higher for summer than for winter crops (Allen et al. 1998). Second, the peak demand of summer crops extends from July to August (i.e. during the dry season), while the peak demand of low water-demand crop happens in spring (i.e. during snow melting and rain seasons).

Water within the irrigation systems of the RAA project is managed by Water User Associations (WUA), which include a chapter of all farmers and their representatives respectively, and also an executive committee, a president, a secretary and a conflict solving committee. The WUA presidents represent the associations in a second order organization called "Comunidad General de Riegos del Alto Aragon" (GCRAA), which coordinates water allocation among the systems. Finally, there is the water agency ("Confederacion Hidrografica del Ebro"), which is responsible for managing the reservoirs and guaranteeing that both the irrigation systems within the RAA project as well as other systems within the Gallego and Cinca watersheds are served the water that corresponds to them according to a system of water use rights.

There are two types of water use rights in the RAA project. "Partial" water use rights entitle their holders to use water as far as there is no scarcity, while "full" water use rights are not conditional on resource conditions.

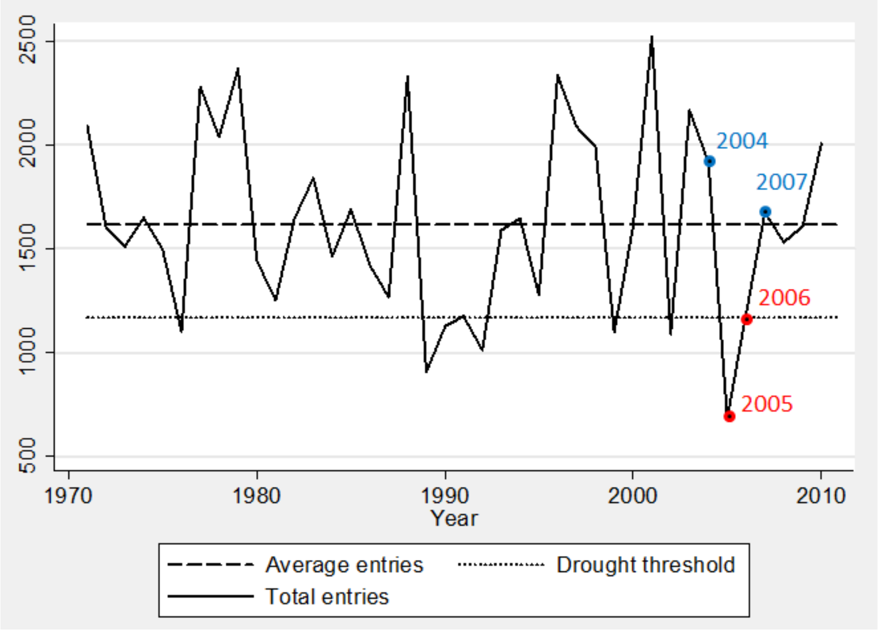
Water from the reservoirs is allocated among the RAA irrigation systems via a water request system. According to this system, the WUAs have to make water requests to the GCRAA on a daily basis. Then the GCRAA sends a unified water request to the water agency, which manages the reservoirs accordingly. Guards employed by the water agency and the GCRAA are in charge of distributing the water across the systems, and then the WUAs are responsible for distributing the water among the farmers. In a fair number of systems, the WUAs also employ field guards to coordinate that process.

Finally, the GCRAA is responsible for issuing rights to use water from the drainage system. Drainage water rights can represent from ten to thirty percent of the water supplied via the conveyance canals in some systems. During droughts, the proportions can even reach forty percent[1].

Droughts and drought management in the RAA project

The most recent evidence of the increase in frequency, uncertainty and severity of water shortages in the RAA project and the broader area was the drought of 2005.[2] The drought manifested mostly during the 2005 and 2006 irrigation campaigns. By 2007 water availability levels had returned to pre-2005 levels.

Figure 2. Series of total water inflows into the RAA reservoirs (hm^3)



Source: Data obtained from Ebro water agency
Note: Series calculated from October to September of each year.

Figure 2 displays a series of the sum of water inflows into the reservoirs of the RAA project over the 12 months that go from the end of one irrigation campaign to the end of the following one. The lower bound line (~1,200hm^3) represents one standard deviation below the series mean which here it is used as an approximate threshold for water deficit[3].

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[1] The drainage water in those systems is not directly appropriated by farmers is but managed by the WUA, which distributes it among all the members through the water allocation process.

[2] During the current 2012 year another extremely severe drought is hitting the RAA system.

[3] The most frequently applied quantitative definition of a drought is based on defining a threshold, below which water availability is considered as a drought. The method is relevant for storage/yield analysis and is associated with hydrological design and operation of reservoir storage systems (Hisdall and Tallaksen 2000). In some applications the threshold is a well-defined flow quantity, e.g. a reservoir specific yield. It is also possible to apply low flow indices, e.g. a percentage of the mean flow or a percentile from a time series distribution. In this study, the threshold is one standard deviation below the1971-2010 series mean. As it

According to the figure, the total reservoir entries were lower than the drought threshold in 1976, 1989-1992, 1999, 2002 and 2005-2006. Out of those years, 2005 stands out with the minimum score.

Table 1 shows a detailed analysis of the magnitude of the 2005 drought as compared to the data series before 2004. As shown in the table, the reservoir entries in 2005 represented around 35 percent of the entries in the previous year and around 40 percent of the average entries in the series. The drought was also patent during the 2006 year. Reservoir entries were around 70 percent of the series average entries and below the approximate 1,200hm^3 water-deficit threshold). Both the 2005 and 2006 decreases in water availability were significant at the 1 percent level. By 2007 water entries were not significantly different than the series average.

Table 1. Univariate sample test of total reservoir water entries from October to September

Years	**Total entries (hm^3)**	**Percentage change[1]**	**T statistic[1]**
1971-2003	1,640		
2004	1,915	+16 percent	-3.5***
2005	685	- 60 percent	12.11***
2006	1,186	- 28 percent	5.74***
2007	1,673	+ 2 percent	-0.42

[1]: Each score is compared to the mean of the 1971-2003 series.

The quota system

As a response to droughts the CGRAA has traditionally used a “quota” system. When quotas are used, the CGRAA divides the reservoir water among the irrigation systems on a per hectare basis (i.e. at a particular m^3/ha rate). Quotas are allocated at the beginning of the irrigation campaign, depending on the water that is available in the reservoirs and estimations of snow melting. Land with partial irrigation rights is left out of the computation of each system’s quota. Once the quotas are allocated, the WUAs are responsible for managing them. Specifically, the quotas enable the WUAs have access to the water and manage it among its members; however, associations do not have the right to sell or give away shares of their quotas to other systems.

In most of the irrigation associations farmers are also assigned an m^3/ha quota that they can manage according to their needs. Specifically, the quota gives farmers the right to access to water but not to exclude others from it. This means that the individual quotas that are not used by farmers are reallocated by the WUA among the rest of farmers in the system. In

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happens, the threshold (1,200 hm3) has also substantive meaning because it is very similar to the average consumption of water by the RAA system and other irrigation systems that are also supplied water from those reservoirs (approximately 1,500hm3; CHE 2000).

this regard, quotas within irrigation systems are used more as an information mechanism for farmers to estimate the maximum of water they can count on for the campaign rather than as a water allocation system.

Finally, quotas can evolve. During the irrigation campaign the water agency and the CGRAA coordinate on a bi-weekly basis to update the quota depending on the evolution of the balance between reservoir water entries and water orders. The specifics of how the quotas are updated have changed over time. In the most recent version of the system (i.e. since 2002) new available water is allocated among the systems on a consumption basis. The quota of each system is updated according the system's average consumption during previous campaigns of normal water availability conditions.
As a recent institutional innovation, farmers are allowed to redistribute their quota across their plots even if the plots are located in different irrigation systems, i.e. WUAs can exchange quotas as far as the exchange is requested by a farmer that cultivates land in the corresponding systems. Such request has to be formulated at the beginning of the campaign and is not reversible.

Finally, some irrigation systems also use other water related rules and measures of their own. During the drought of 2005, for example, some irrigation communities extended monitoring duties of the field guards (e.g. overnight patrolling, and intensification of daylight patrolling).

THEORY

From a political economy approach, water in an irrigation system is an example of a common pool resource (CPR), i.e., is difficult to partition for private consumption and can be depleted (V. Ostrom and E. Ostrom 1977).

Much of the research on CPR management has observed provision and appropriation problems in the context of overexploitation situations like the one illustrated by the "tragedy of the commons" (Hardin 1968). Provision problems manifest through the inability of individuals to produce the resource or the required infrastructure for its use. Appropriation problems are reflected in the incapacity of resource users to self-restrain consumption when it is needed. According to the "tragedy of the commons", CPR users do not have the incentives to self-restrain resource extraction because they cannot exclude others from the benefits of such effort, so the resource system is overexploited and ultimately collapses.

The theory of the commons focuses on common property regimes as one way to cope with the tragedy of the commons. In common property regimes, provision and appropriation problems are solved via the development rules and norms that guarantee cooperation among individuals. Both the development of those rules and norms and the continual adherence of individuals to them are necessary to avoid collective action problems over time (Ostrom 1990, Ostrom et al. 1994).

According to the theory of the commons a number of institutional and social factors can contribute to continual cooperation in CPR regimes (Poteete et al. 2010). Three of the most cited arrangements in institutional studies of CPR regimes are bottom-up collective choice, clear boundaries, and monitoring (Ostrom 1990, Cox et al. 2010). Bottom collective choice institutions allow direct users of the CPR to participate in the design and modification of the rules that govern their use of the resource. Direct users have first-hand and low-cost access to information about the resource use and thus enjoy a comparative advantage to design effective rules that are tailored to their contexts (Berkes 2001). Additionally, enabling the participation of direct users in rule development can facilitate the legitimacy and endorsement of the resulting rules (Ostrom 1990, Ostrom 2005, Subramanian et al. 2007).

The existence of strong physical and social boundaries around a resource contributes to internalize the positive and negative externalities produced by users, which helps guaranteeing that those who bear the costs of cooperating are the ones who receive the benefits (Ostrom 1990). More specifically, strong property rights facilitate excludability of individuals who are not bounded by current or potential cooperation rules (Cox et al. 2010), and can contribute to the emergence and endurance of norms of reciprocity and trust among community members (Gibson and Koontz, 1998).

Finally, "monitoring makes those who do not comply with rules visible to the community, which facilitates the effectiveness of rule enforcement mechanisms and informs strategic and contingent behaviour of those who do comply with rules" (Cox et al. 2010, 37). In some cases monitoring emerges at a low cost through informal interactions among resource users, like when farmers along an irrigation canal use the water one after the other (Trawick 2001, Cox 2010). In some other cases monitors can be hired. The effectiveness of monitoring in both cases depends on the benefits that those who monitor receive from identifying rule violators or the conditions of the resource.

Two of the most well studied social factors contributing to sustained CPR regimes are group size and leadership (Poteete et al. 2010). Although nuanced by empirical evidence (Poteete and Ostrom 2004, Varughese and Ostrom 2001), theory posits that the costs of monitoring those who do not comply with rules or agreements increases with group size, thus reducing the chances of cooperation (Olson 1965, Ostrom et al. 1994). Additionally, coordination and decision making in large groups may entail high information and negotiation costs and discourage users from collaborating (Lubell et al. 2002, Poteete and Ostrom 2004).

Leaders, on the other hand, can assist resource users to form agreements, rules or strategies to cope with the resource conditions, as well as perform more general functions such as trust building, conflict management, knowledge diffusion, and mobilization of users for change (Meinzen-Dick et al. 2002, Subramanian et al. 2007, Folke et al. 2005). Leadership's authority can be based on education and experience (Meinzen-Dick 2002), differences in wealth (Velded 2000, Baland and Platteau 1999) and/or formal organizational positions. In all cases, however, it is important that leaders are accountable to users, as power misuse can weaken trust on the CPR regime and its effectiveness (Theesfeld 2009).

The hypotheses that drive the analysis are:

H1. The robustness of irrigation systems increases as the number of users decreases.
H2. Irrigation systems that enjoy more participatory collective choice processes will be more likely to be robust to droughts than otherwise.
H3. The robustness of irrigation systems to droughts increases with the experience of the leaders of the communities that manage them.
H4. Irrigation systems with strong monitoring systems will be more likely to be robust to droughts than otherwise.
H5. Irrigation systems that enjoy flexible water use rights will be less likely to be robust to droughts than otherwise.

All hypotheses are drawn from the theory reviewed in this section. Hypothesis 1 captures the negative relationship between group size and collective action: larger numbers of resource users face increased transaction costs, which in turn discourages collaboration as well as the enforcement of association rules. Hypotheses 2, 3 and 4 are drawn from the institutional studies on CPR regimes. Clear boundaries (H5) facilitates the allocation of costs and benefits of cooperation, while bottom-up collective choice (H2) and monitoring mechanisms (H4) contribute to the effectiveness and legitimacy of collective courses of action and rules, and compliance of users.

METHODS

Research design and case selection

To test the hypotheses of the study, I rely on a pseudo-experimental, pre-post-test research design (Shadish et al. 2002). In this study's design, the drought of 2005 is used as a treatment. This is possible because the drought affected all the irrigation systems of the RAA system simultaneously. Additionally the research design enjoys the controlled environment provided by the quota system. The quota system can be seen as an asset for the analysis because it controls for the fact that there are biases in the water allocation among WUAs that enable some communities to get proportionally more water than others.

The case selection was not random by design. Case selection was purposive and aimed to include the entire population of 50 irrigation systems within the RAA project. Due to data availability, however, the sample was reduced to 38 of them. Missing data was distributed across a number of variables, including both the dependent variable and independent variables. As it is shown in the Appendix 1, the sample and missing data groups were not statistically different with regard to any of the independent variables. Thus, although not random by design, the sample still enabled inferential statistics without evident threats to internal validity.

Calculation of variables

The analysis of this study relies on three regression models, each of which explains a different dependent variable.

The 3 dependent variables of the analysis, however, are based on the same index, i.e., a seasonal index of irrigation performance (Annual Relative Irrigation Supply Index –ARIS; Salvador et al. 2011), which consists of a ratio between the water that is applied to crops and the water that the crops need in an irrigation system.

$$\text{ARIS}^{4} = \frac{\text{Irrigated Water}}{\text{Crop Water Needs}}$$

Three of the dependent variables are calculated as the difference between the ARIS in 2004 and the ARIS in 2005, 2006 and 2007 respectively. The calculation of the dependent variables as differenced ARIS aims to control for pre-existing performance levels[5] across the irrigation systems as well as unobserved area effects that determine the ARIS level, like the efficiency in the application of water at the plot level or aspects related to the physical conditions of the canals.

Finally, the ARIS differences were calculated in percentage scores. Negative scores for a particular year thus mean a relative decrease in performance as compared to the reference year (either 2004 or 2005), and positive scores means the opposite.

Table 2 covers the operationalization of the explanatory variables used in the statistical analysis and their expected relationship according to the hypotheses.

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[4] For a detailed explanation of the factors included in this calculation see Appendix 2. Assuming a 100percent efficient application of water to crops, an ARIS value of 1.00 means that the crop is not being under- or over-irrigated. However, 100percent application efficiency cannot be assumed under commercial field conditions. According to Clemmens and Dedrick (1994, cited in Lecina et al. 2010) in an optimistic scenario, the best systems attain 90percent efficiency. Under this scenario an appropriate ARIS value is 1.1. Scores below that number would point to crop stress.

[5] An alternative to control for preexisting performance levels would be to use lagged values of ARIS; however, that would also introduce potential problems of autocorrelation (Rabe-Hesketh and Skrondal 2008).

Table 2. Measurement of explanatory and other independent variables and expected effect on performance change.

Variable	**Measurement**	**Scale**	**Effect**
Biophysical and social Variables			
Hydric Soils	Percentage of land in an irrigation system with hydric soils (i.e. soils with water retention capacity -clay loam and silty clay loam)	Interval	+
Group Size (H1)	Number of farms in an irrigation system	Interval	-
Governance Variables			
Local Collective Choice (H2)	Average participation in the last 10 years as per the percentage of the irrigation system's surface that is cultivated by attendants	Interval	+
Leadership (H3)	Tenure in years of president of irrigation association	Interval	+
Monitoring (H4)	Whether the irrigation system has a field guard	Binary (1=Yes)	+
Flexible boundaries (H5)	Percentage of land in an irrigation system with partial water use rights	Interval	-
Drought-related Variables			
Drought-monitoring	Whether the guard in the irrigation system implemented extra monitoring measures during the 2005 drought	Binary (1=Yes)	+
In-water transfers	Percentage of the irrigation system's land that received water from other irrigation systems via the quota transfer system.	Interval	+
Drainage water (C)	Whether the irrigation system receives water from the drainage system on a permanent basis	Binary (1=Yes)	(control)

Note: C = Control Variable

Data Collection

To characterize the 2005 drought, monthly water storage records from the two main reservoirs that provide water to the area were obtained from the *Ebro River Water Agency* (CHE).

Data to construct the ARIS were collected from governmental organizations and the GCRAA. Monthly meteorological data were obtained from a series of weather stations that are distributed across the area of study and managed by the *Spanish Meteorological Agency* (AEMET). Crop data at the farm level were obtained from the *Regional Government of Aragon* (DGA). Data on water consumed by the irrigation systems were obtained from the GCRAA.
Most of the data to construct the independent variables were collected via a survey. The survey was addressed to the president or secretary of the 50 WUAs that belong to the RAA project via mail, and collected by phone to guarantee a 100 percent response rate. Although the survey's response rate was 100 percent, not all the WUA representatives were able to provide all the information requested, so there are missing data.

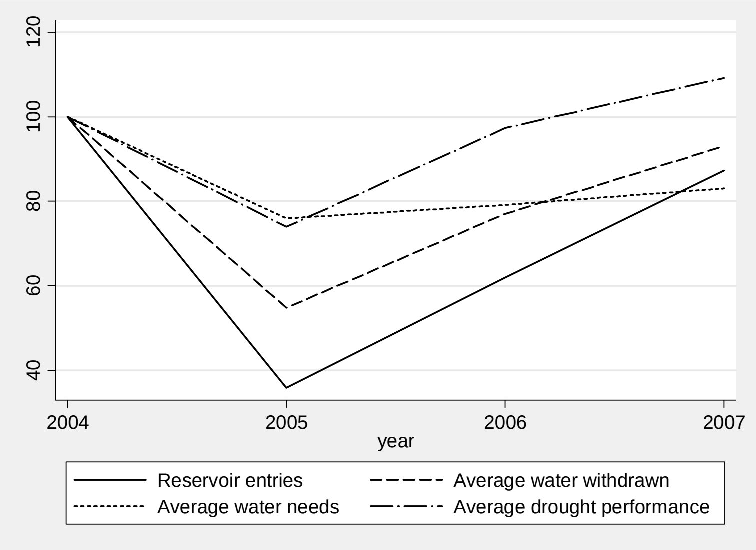
Finally, the *drainage water* variable was used as a control in the analysis for reasons related to data collection. As it happens, there are no records about how much water the systems appropriate from the drainage system. This means that those amounts are not included in the calculation of the ARIS, and thus the ARIS may not fully reflect the actual performance of the systems that enjoy drainage water. Fortunately the GCRAA does count on a register of drainage water rights that specifies whether the systems use the drainage water on a temporal or permanent basis. The register was ultimately used as the data source to construct the variable.

RESULTS

Preliminary findings

Figure 3 shows the abovementioned dramatic decrease in the water that entered the reservoirs of the RAA system from 2004 to 2005 (around 65 percent). Similarly, average water consumed by the RAA systems was also reduced dramatically (more than 40 percent). The average system performance of the RAA system (ARIS), however, decreased much less (less than 25 percent). Part of this can be explained by the fact that the water needs were also reduced on average (by a bit more than 20 percent). the RAA water needs also decreased. This seems to correspond with a reduction in the RAA water needs (up to a bit more than 20 percent).

Figure 3. Percentage change of reservoir entries and average system performance in the RAA system (2004-2007)



Source: Data obtained from Ebro water agency
Note: All measures but the "reservoir entries" are calculated by aggregating irrigation system data (n = 38). The base year is 2004.

Table 3 shows a more formal look at performance in the RAA system. According to table 3-4, average system performance decreased to 0.87 in 2005. The change is significant but is less than 20 percent below the theoretical threshold of no crop stress (ARIS=1.1; assuming irrigation efficiency of 90 percent). The 0.87 performance score seems acceptable considering that slight crop stress does not automatically result in crop yield losses. The score also seems acceptable with regard to values reported in previous studies within the area, which range between 0.57 and 2.05 (Salvador et al. 2011). More importantly, the score represents a 25 percent decrease in performance from 2004 to 2005, which is notable considering that water availability decreased by 65 percent (around 60 percent if compared to the average water availability from 1971 to 2003).

Table 3. Paired t-tests of system performance in the RAA project (2004-2007)

	Average system performance (not differenced)		
	Mean	t-score (base=previous year)	t-score (base=2004)
2004	1.16		
2005	0.87	8.95***	
2006	1.13	-6.22***	0.63
2007	1.27	-3.4***	-2.13**

* *p*<0.1; ** *p*<0.05; *** *p*<0.01
n=38
Note: One-tailed test

Overall, the results point to the relative ability of the RAA system to absorb the impact of the drought. It can thus be argued that the quota policy had a positive effect on the robustness of the system. Everything being equal, had the quota not have any positive effect on performance we should have expected a decrease in performance by around 65 percent from 2004 to 2005. The fact that the RAA system's performance only decreased by 25 percent indicates that the system was able to mitigate 35 percent of the drought impact.

Regression results

Table 4 provides the OLS estimates of three models. Model 1.a includes the main explanatory variables of the study and the variable that controls for the 8 systems that permanently withdraw water from the drainage system. Model 1.b adds the two drought-related variables. Model 1.c tests the robustness of the results by including only the explanatory variables that were significant in Model 1.a.

None of the models violates OLS assumptions. The Breusch-Pagan/Cook-Weisberg test fails to reject the null hypothesis of homoskedasticity, the Ramsey RESET fails to reject the null hypothesis of linear specification, and the mean VIF and CI do not indicate the existence of strong multicolinearity issues.

Table 4. OLS for Robustness to the 2005 drought
(Dependent variable: Percentage difference between performance in 2005 and in 2004)

	Model 1.a	Model 1.b	Model 1.c
Hydric soils	0.146	0.262	0.201
	(0.085)*	(0.097)**	(0.078)**
Association size	-0.008	0.011	
	(0.020)	(0.021)	
Leadership	1.715	2.072	1.839
	(0.658)**	(0.649)***	(0.640)***
Collective choice	-0.057	-0.005	
	(0.090)	(0.089)	
Formal monitoring	11.620	10.547	9.663
	(5.862)*	(5.889)*	(4.906)*
Flexible boundaries	1.598	1.514	1.606
	(0.373)***	(0.360)***	(0.345)***
Drainage water	-7.941	-5.090	
	(4.518)*	(4.482)	
Drought monitoring		-10.274	
		(5.129)*	
In-water transfers		1.643	
		(0.936)*	
Constant	-46.644	-60.863	-54.154

	(10.640)***	(11.924)***	(8.234)***
Adjusted R^2	0.41	0.46	0.40
Sample size	38	38	38
F (4, 33)	4.63	4.54	7.12
Breusch-Pagan/Cook-Weisberg’s χ^2	1.58	1.6	1.2
Mean Variance Inflation Factor (VIF)	1.48	1.71	1.26
Condition Index (CI)	16.6	20.75	10.57
Ramsey RESET’s F’s	1.01	0.7	0.85

* $p<0.1$; ** $p<0.05$; *** $p<0.01$
Note: a negative coefficient means that the corresponding variable is related to a percentage decrease in irrigation performance (as per the year of reference), while a positive coefficient means the opposite.

Model 1.a explains 41 percent of the ARIS change from 2004 to 2005. The *association size* variable in Model 1.a is not significant but the *hydric soils* variable is positive and significant. An extra hectare with hydric soils in a system is likely to increase drought performance by 0.15 percent.

Also, all the governance variables but *collective choice* have a significant effect on the dependent variable. The *formal monitoring* variable has one of the strongest impacts. Everything being equal, irrigation systems that count on the monitoring duties of a field guard are expected to have on average an approximately 12 percent higher ARIS during drought than irrigation systems without guard. Also, *leadership* has a relatively strong impact, as each additional year of tenure of an irrigation system’s president is likely to increase in more than 1.7 percentage points the performance of the irrigation system during droughts. Contrary to expectations, the *flexible boundaries* variable has a positive relationship with performance. An extra percentage point of land with partial irrigation rights is likely to increase performance during droughts by 1.6 percent. The positive effect may be explained by the fact that quota adjustments during the irrigation campaign are calculated according to the systems’ consumption during previous years of no drought. As explained in the background sections, land with partial water rights is entitled to use water during no-drought periods but not during drought periods. Thus, systems with higher percentages of land with partial water rights would be benefiting proportionally more from the quota adjustments that systems with lower percentages. Also, as the GCRAA meeting minutes illustrate, the fact that quota adjustments are based on consumption constitutes an incentive for farmers to over-appropriate during no-drought periods. According to the model results, that incentive would be aggravated in systems with higher percentages of land with partial water rights.

Finally, the *drainage water* variable shows a negative and significant effect on drought performance. This means that irrigation systems that benefit from the drainage water on a permanent basis, do it proportionally more during drought periods than during no-drought periods. In other words, the fact that water in the RAA system can be effectively reused needs to be taken into account to explain drought performance in the RAA system.

Model 1.b includes the variables in Model 1.a and also the *in-water transfers* and *drought monitoring* variables. These measures were not included in the hypotheses but were expected to be important to understand robustness to droughts in the case of the RAA system. By including them in the analysis, Model 1.b enables checking for the robustness of the results in Model 1.a, i.e. to control for possible ways in which the variables in Model 1.a are non-randomly assigned. The model explains 46 percent of the ARIS change from 2004 to 2005. The first of the two variables is positive and significant. A 1 percent increase in the land that receives water via the quota transfer system is likely to result in a 1.6 percent increase in drought performance. This effect is less intuitive than it seems. At the end, farmers still have to make their cropping decisions and they could perfectly grow more crops than appropriate, even after discounting the water that they could get from other systems. One explanation is that farmers who use the transfer system are also subject to a closer monitoring by the WUAs, as they have to request the transfer formally and be accountable for it. A similar explanation is that, in having to request the quota transfer, the farmers adjust better the water that they need to the crops that they are planting.

Alternatively, extended monitoring duties during droughts have a negative and also pretty strong impact on performance. This last result is counterintuitive, particularly with regard to the positive impact of the *monitoring* variable. A pretty plausible explanation is that the causal arrow runs in the reverse direction from what was hypothesized, i.e., that decreases in the performance during droughts motivate irrigation systems to strengthen monitoring in an attempt to bring performance back up. In a study of forest regeneration in 9 countries, Chhatre and Agrawal (2008) found a negative relationship between monitoring and sanctioning and forest conditions and reached a similar conclusion, i.e. that villagers were more likely to hire guards and impose fines if their forest were in not a good condition than otherwise. The reverse causality argument makes even more sense in the RAA case after considering that strengthening monitoring during droughts is not a rule or strategy that pre-exists drought periods but just an ad hoc measure that some irrigation systems developed during the drought of 2005.

All in all, the sign and significance of the explanatory variables (*hydric soils*, *leadership*, *formal monitoring* and *flexible boundaries*) does not change dramatically from Model 1.a to Model 1.b indicating that even if there were collinearity between those variables and the two added variables, those interactions dot not strongly affect the results.

Finally, Model 1.c includes only the four explanatory variables that were significant in Model 1.a. The model still explains 40 percent of the variation in performance change between 2004 and 2005. Also, none of the coefficients of the included variables changes significantly as compared to those in Models 1.a and 1.b.

Table 5. OLS for ARIS change between different pairs of years

	Model 1.a (2005-2004)	Model 2 (2006-2004)	Model 3 (2007-2004)
Hydric soils	0.146	0.249	0.037
	(0.085)*	(0.162)	(0.202)
Association size	-0.008	0.019	0.022
	(0.020)	(0.038)	(0.046)
Leadership	1.715	-0.199	0.907
	(0.658)**	(1.151)	(1.266)
Collective choice	-0.057	-0.168	-0.139
	(0.090)	(0.173)	(0.211)
Formal monitoring	11.620	19.182	7.416
	(5.862)*	(11.007)*	(13.785)
Flexible boundaries	1.598	0.665	-0.130
	(0.373)***	(0.720)	(0.800)
Drainage water	-7.941	-7.657	-6.238
	(4.518)*	(8.716)	(10.667)
Constant	-46.644	-23.522	3.880
	(10.640)***	(20.358)	(25.492)
Adjusted R2	0.41	0.13	0
N	38	38	38
F (4, 33)	4.63	1.82	0.41
Breusch-Pagan/Cook-Weisberg’s χ^2	1.58	0.00	0.12
Mean Variance Inflation Factor (VIF)	1.48	1.45	1.45
Condition Index (CI)	16.06	16.4	16.69

Ramsey RESET’s F’s	1.01	0.66	1.37

* $p<0.1$; ** $p<0.05$; *** $p<0.01$

[1]: 2005 was already in drought so from 2005 to 2006 there was no change.

[2]: The quota was activated in 2005 but not in 2006 so there was a change in that regard.

Note: a negative coefficient means that the corresponding variable is related to a percentage decrease in irrigation performance (as per the year of reference), while a positive coefficient means the opposite.

Table 5 contains Model 1.a from table 4 and two comparable models that test the hypotheses using reference years other than 2004. Like in Models 1.a to 1.c, post-estimation tests showed no violations of the OLS assumptions. Model 2 aims to explain performance in 2006 as compared to performance in 2004. As explained above, 2006 was still a drought year. Thus, Model 2 aims to capture the effect of the explanatory variables under the second year of drought. The model explains 13 percent of the variation in the dependent variable. According to the model, only the *monitoring* variable shows a significant effect. Everything being equal, irrigation systems that count on the monitoring duties of at least one field guard are expected to have on average an approximately 20 percent higher ARIS during drought than irrigation systems without guard. Also, the coefficients of the *hydric soils* variable is not significant (p-value = 0.13) but is notably bigger than the corresponding coefficient in Model 1.a. Alternatively, the coefficients of the *flexible boundaries* and *leadership* variables are notably smaller than those of Model 1.a. Finally, Model 4 aims to explain performance in 2007 as compared to performance in 2004. The model aims to capture the impact of the explanatory variables in the absence of drought and quotas. The model does not explain variation in the dependent variable and the coefficients of all explanatory variables that were significant in Model 1.a are now notably smaller.

DISCUSSION

The discussion section is structured around a series of questions that aim to unveil the complexity behind the regression results. The section starts with a review of the main findings and then continues with an exploration of relevant interactions between independent variables that were not covered in the previous section.

Why are the leadership and flexible boundaries variables only effective in the first drought year?

The change in the effect of leadership and flexible boundaries variables from model 1.a to Model 2 can be related to the fact that in 2006 the quota system was not activated. According to this, the importance of the above variables significantly decrease in the in the absence of quotas, i.e. is contingent to the implementation of the quota policy.

The lack of effect of the *flexible boundaries* variable in the absence of quotas can be explained with regard to the consumption-based criterion used to adjust the quotas during the irrigation campaign. Basically, in the absence of quotas, the comparative advantage of systems with higher percentages of land with partial water rights disappears and so does the impact of the variable on drought performance.

The lack of effect of the *leadership* variable in the absence of quotas can be interpreted with regard to the role fulfilled by the presidents of the WUAs. During droughts, one of the most important tasks of the presidents is that of transmitting information from the GCRAA to the farmers about water reserves and the quota allocations. In that role, the presidents are also responsible for framing farmers' cropping decisions at the beginning of the irrigation campaign so there are no issues of crop stress during the campaign. The tenure of presidents provides them not only expertise abut also authority to fulfill that framing role.

The role of presidents is complemented in many systems by the role of field guards. As presented in the background sections guards in many irrigation systems constitute the very center of action of the water allocation process. Thus, contrary to presidents, field guards have to deal with farmers on a daily basis during the irrigation campaign and thus are more able to fulfill monitoring duties as well as to solve issues among farmers on the spot. Overall, both presidents and guards fulfill an important role to understand drought performance. The role of presidents, however, seems to be more contingent on the top-down activation of the quota system and its follow up during the campaign than that of guards, which are responsible for the ultimate performance of the water allocation process in the field regardless of the existence of quotas and even droughts.

Why are the group size and collective choice variables not significant?

As mentioned above, the results do not support the claim that collective choice or group size contribute to drought robustness. The lack of effect *group size* can be related to its interaction with *monitoring*. As shown in Appendix 3 the average size of systems with a field guard is more than twice the size of systems without a guard. The difference is significant at the 1 percent level and is also supported by theory. As indicated in the theory section, farmers in larger user groups face higher transaction costs and thus are confronted with lower incentives to cooperate than farmers in smaller groups (Poteete et al. 2010). In the RAA system, farmers in larger group systems would be confronted with higher costs of reciprocal monitoring, which in turn would justify the need to hire a guard. Interestingly enough, the comparative advantage of smaller systems in terms monitoring costs might turn into a disadvantage during droughts, as the existence of a guard can indeed make a difference in those conditions. Overall, it is possible that the theoretically positive effect of group size on performance is counterbalanced by the lack of formal monitoring mechanisms during droughts.

The lack of effect of the *collective choice* variable can also be linked to the *monitoring* variable. Collective choice tends to be significantly higher in systems with monitoring than in systems without (see Appendix 3). Thus, it is statistically possible that the potentially positive effect of collective choice is counterbalanced by the lack of formal monitoring mechanisms (Ostrom 1990, Anderies et al. 2004).

This effect is less intuitive than it seems. At the end, farmers still have to make their cropping decisions and they could perfectly grow more crops than appropriate, even after discounting the water that they could get from other systems.

CONCLUSIONS

This study aimed to add to the understanding of the conditions that enhance robustness to droughts by studying the performance of *Riegos del Alto Aragon* (RAA) irrigation project, a large system of irrigation systems located in northeastern Spain. For that purpose, the study tested 5 hypotheses from the theory of the commons via a series of OLS models.

According to the results, monitoring, leadership and flexible boundaries notably contribute to robustness to droughts at the system level. Although in different ways, the three variables confirm the usefulness of applying the theory of the commons to understand robustness to disturbances (Agrawal 2001, Poteete et al. 2010, Cox et al. 2010). According to theory, monitoring contributes to enduring rule compliance and the stability of common property regimes (Coleman and Steed 2009, Cox et al. 2010). The positive impact of the monitoring variable on drought performance found in this study supports that claim, and suggests that such function can be particularly relevant during stress situations like those triggered by droughts. The negative relationship found between performance and the strengthening of monitoring during droughts also supports that interpretation.

Evidence regarding the leadership and flexible boundaries suggest that the impact of those factors is contingent on the presence of higher level operational rules, i.e., the quota system. The activation of the quota system to cope with droughts, would be reinforcing the authority of WUA presidents to promote farmers' cooperative behavior vis a vis cropping and water use. Alternatively, the interaction between the flexible boundaries and the quota system would be promoting rent seeking behavior. The adjustment of the quotas according to consumption in previous years constitutes an incentive for systems to over-appropriate during no-drought periods. This incentive would be aggravated in systems that have higher percentages of land with partial waters rights, as that land is entitled to use water during no-drought periods but not during drought periods. Overall the above interactions are illustrative of the importance of taking into account multi-level governance when studying social-ecological phenomena (Ostrom 2007, 2009, McGinnis and Ostrom forthcoming).

Other variables like the existence of hydric soils and the import of water from other systems were also positively related to drought performance. The impact of the first variable shows the importance of taking in to account the role of bio-physical variables to understand social-ecological phenomena like robustness to droughts (Levin et al. 1998, Berkes and Folke 1998, Ostrom 2007, 2009). The impact of the second variable shows the importance combining strong property rights with mechanisms that allow for flexibility in the allocation of water if necessary. More broadly, the two findings illustrate the need to understand natural resource management in its context and the possibility of combining multiple policy solutions so solve environmental problems (Ostrom 2007).

Collective choice and group size did not have any impact on robustness to drought. That result can be interpreted with regard to additional evidence the theory of the commons. The moderately negative relationship between formal monitoring and group size suggests that smaller group systems would enjoy more efficient farmer-to-farmer monitoring and be less in need of other monitoring mechanisms during no-drought periods than larger-group systems; the lack of other monitoring mechanisms, however, would in turn make small-group systems more vulnerable than larger-group systems to water allocation issues during stressful situations like those triggered by droughts. Also, the moderately negative interaction between monitoring one hand and collective choice and group size on the other suggests that the relatively low transaction-costs among farmers in small-group systems would not only discourage the use of monitoring other than farmer-to-farmer supervision, but also encourage bottom up collective choice. Ultimately, the lack of appropriate monitoring mechanisms during droughts would be cancelling the potentially positive effect of collective agreements and information sharing.

Overall, the findings with regard to leadership, flexible boundaries, collective choice and group size point to the interest of using theory and substantive knowledge to interpret interactions within basic sets of explanatory variables to disentangle the complexity behind phenomena (Achen 2005). Finally, the findings show the relevance of using and adapting the theory of the commons to understand sustainability issues other than those embodied in overexploitation issues. The theory was useful to both explain the regression results as well as interpret additional quantitative and qualitative evidence. The distinction between different appropriation situations as well as the observance of multi-level and other interactions was particularly helpful in that regard, and sheds light on a path to further test and build theory on robustness to droughts and other disturbances.

APPENDICES

Appendix 1.Descriptive statistics and normality tests

Table A1 provides cross-sectional summary statistics for all the independent and dependent variables, as well as mean-difference tests comparing the sample and the missing data groups. As shown in the table, means of the sample and missing data group are not statistically different in terms of independent variables or almost all of the dependent variables of the analysis. The average ARIS change from 2005 to 2006 was different for the sample group and the missing data group. Although not particularly meaningful (the size of the missing data group is just 4 systems), inferences from the model based on that variable may need to be interpreted with additional caution.

Table A1 Comparison of sample and missing data-group means (2005)

Variable Name	**Sample group**					**Missing group**		**t-test**[1]
	N	**Min.**	**Max**	**St. Dev.**	***Mean***	**N**	***Mean***	
Independent Variables								
Hydric Soils	38	0	97	25.39	*48.9*	9	*38.9*	-0.92
Size	38	12	565	114.6	*158*	12	*161*	0.07
Collective Choice	38	19.3	90.4	20.8	*46.7*	6	*47.2*	0.06
Leadership[2]	38	0	14	3.28	*3.6*	10	*4.7*	0.93
Monitoring	38	0	1	0.41	*0.79*	12	*0.67*	-0.85

Flexible boundaries	38	0	27.1	5.34	*3.9*	12	*2.28*	-0.98
Drought monitoring	38	0	1	0.45	*0.26*	11	*0.36*	0.63
In-water transfers	38	0	7.8	2.2	*3*	12	*3.5*	0.57
Drainage water	38	0	1	0.43	*0.23*	12	*0.08*	-1.15
Dependent Variables								
ARIS change (2005-2004)	38	-49.6	7.53	13.9	*-23.9*	4	*-32.2*	-1.15
ARIS change (2006-2004)	38	-60.2	44.4	22.04	*-1*	4	*-0.5*	0.05
ARIS change (2007-2004)	38	-43.4	55.9	23.6	*10.6*	4	*7.02*	-0.28
ARIS change (2006-2005)	38	-37.3	90.3	27.7	*31.6*	4	*51.7*	1.13*

* $p<0.1$; ** $p<0.05$; *** $p<0.01$

[1]= One tailed t-test

Note: Means of dummy variables (drainage water, drought monitoring, monitoring) represent percentages of systems with the attribute.

[2]= Leadership is the only variable that varies over the years used for the analysis (2005-2007). The means comparison was also performed on average for those years. The means difference was not significant either (sample group=4.2; missing variables group=4.8; t-test=0.48). An outlier belonging to the missing group had to be removed for both the 2005 and the 2005-2007 means comparisons. The outlier scored 25 on average (the second highest average leadership score was 15, and the average of the missing group= 6.7). If not removed the difference between the 2005-2007 means across groups was significant at the 10 percent level (sample group=4.2; missing variables group=6.6; t-test=1.62).

Normality tests for the dependent variable pointed to the existence of an influential outlier ARIS change from 2004 to 2005= +52 percent) that could bias the results. After removing the outlier the normality tests resulted in the non-rejection of the null hypothesis of normality (see tables A2 below for detailed results).

A2.1. Normality tests for "ARIS change (2004-2005)" variable

	Before removing the outlier	After removing the outlier
Shapiro-Wilk W	3.2***	-0.8
Shapiro-Francia W'	3.2***	-0.73
Skewness/Kurtosis	17.9***	1.52

n=38

A2.2. Normality tests for "ARIS change (2004-2006)" variable

	Before removing the outlier	After removing the outlier
Shapiro-Wilk W	0.06	-0.4
Shapiro-Francia W'	0.47	-0.08
Skewness/Kurtosis	0.84	0.87

n=38

A2.3. Normality tests for "ARIS change (2004-2007)" variable

	Before removing the outlier	After removing the outlier
Shapiro-Wilk W	0.66	0.43
Shapiro-Francia W'	0.67**	0.43
Skewness/Kurtosis	0.26**	0.14

n=38

A2.4. Normality tests for "ARIS change (2005-2006)" variable

	Before removing the outlier	After removing the outlier
Shapiro-Wilk W	1.3	1.13
Shapiro-Francia W'	1.5*	1.32*
Skewness/Kurtosis	3.41	1.46

n=38

Appendix 2. Variables used in the calculation of irrigation performance (ARIS)

$$\text{ARIS} = \frac{\text{Irrigated Water}}{\text{Crop Water Needs}} = \frac{\text{Irrigated Water}}{\sum_{i}^{k}(NHn * ha)_i}$$

Where:

i = specific crop
k = number of different crops in the irrigation system
NHn = Net Crop Water Needs (in m^3)
ha = hectares

The most important factors that condition *NHn* are the crop evapotranspiration (*ETc*) and the amount of rainfall that can be effectively used by the crop (*PE*) (Tejero 2003). Following Allen et al. (1998), *ETc* was obtained from multiplying a crop water coefficient (*Kc*) and a potential evapotranspiration coefficient (ET_0).

$ETc = ET_0 * Kc$

Kc is a theoretical index of the water that a crop needs depending mostly on the species and life cycle stage (Allen et al. 1998). ET_0 measures the amount of surface water that is removed to the atmosphere due to plant transpiration or direct surface evaporation in a hypothetical reference surface of grass with an assumed crop height of 0.12 m, and a moderately dry soil and radiance reflectance (Allen et al. 1998).

Although the FAO provides *Kc* values of reference on major crops across climatic regions, it has been recommended using site specific *Kc* values whenever available (Allen et al. 1998). Monthly *Kc* values of the dominant crops in the area of study in 1995 were obtained from Martínez-Cob et al. (1998) and used as reference for the period under study. The ET_0 was calculated following the Hargreaves method, as adapted to the study area by Tejero

(2003). Finally, monthly total rainfall data was transformed into PE measures following the method recommended by the *Soil Conservation Service (SCS)* (Dastane 1978, cited in Tejero 2003).

Appendix 3. Averages of explanatory variables by selected groups (2005)

		Hydric soils	**Group size**	**Leader.**[1]	**Collective choice**	**Monitor.**	**Flexible boundaries**	**n**
Monitor	**No**	52.9	73.9[*]	6[#]	55.7[#]	--	5.9	8
	Yes	47.8	181.4	3	44.3	--	3.3	30
Drought Monitor	**No**	44.5[1]	140.8[*]	3.7	48	0.71	4.3	28
	Yes	61.2	209.1	3.4	43	1	2.5	10
Drainage water	**No**	53	155.6	3.7	46.8	0.72[*]	4.1	29
	Yes	35.8	168.9	3.2	46.3	1	3	9

*= Significantly lower than in the comparison group mean; at least 10 percent significance level. One-tailed test.

[#]= Significantly higher than in the comparison group mean; at least 10 percent significance level. One-tailed test.

[1]= The averages for this variable were also calculated for the 2004-2007 period with very similar results.

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