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Does irrigation modernization enhance drought performance? Evidence from a qualitative comparative analysis

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ABSTRACT

The increasing frequency and severity of droughts pose a serious threat to the functioning and sustainability of irrigation systems. Policymakers and practitioners have set forth high expectations that the modernization of irrigation systems would reduce agricultural water demand by increasing the efficiency of water application. How new technologies produce outcomes, however, is strongly interdependent with other variables relevant in the context of community-based irrigation management. Employing a qualitative comparative analysis, our study aims to uncover how modernization, in combination with other irrigation system characteristics, contributes to drought performance of irrigation management, as measured through the satisfaction of farmers with key community governance tasks during droughts. According to the results, micro-irrigation systems employ a relatively lower number of adaptation measures, the majority of which are supply-side oriented. Alternatively, furrow irrigation systems tend to rely on demand-side measures and depend more strongly on assembly participation when a relatively high number of measures are implemented. Our findings echo previous calls for renewed attention to solutions emerging from traditional irrigation systems and nuance irrigation modernization as the major solution to face droughts and water scarcity. The findings advocate for consideration of different responses of water user associations to drought for policy design. Moreover, efforts aimed at modernization should consider their effects on path dependencies, collective action dynamics, and environmental goals.

1. Introduction

Droughts have become one of the clearest manifestations of climate change worldwide (Padrón et al., 2020; Vicente-Serrano et al., 2022) and pose significant challenges to agricultural water management, particularly in arid regions where crop production relies heavily on irrigation. In Spain, where agriculture is responsible for about 82% of total water withdrawals and covers around 66% of cultivated land, droughts are becoming particularly frequent and severe. As a result, adapting to drought has become a central concern in irrigation research, policy, and practice.

In many countries worldwide, irrigation systems are managed by local water user associations (WUAs) (Garces-Restrepo et al., 2007; Ostrom, 1990; Tang, 1992). Such management requires high levels of cooperation among farmers. Research on community-based natural resource management (CBNRM) has improved our understanding of the conditions that enable cooperative natural resource management and how these conditions interact with one another and with socio-ecological conditions (Baggio et al., 2016; Cox et al., 2010; Wang and Chen, 2021). Spain has long been a pioneer in both irrigation agriculture and collective water governance, with WUAs playing a central role in local-level water allocation and drought responses. In the context of droughts, research on the intersection between irrigation governance and drought adaptation is emerging, with the goal of understanding the conditions under which communities can adequately react to such disturbances (Villamayor-Tomas et al., 2020; Villamayor-Tomas and García-López, 2017).

A central theme in CBNRM is the capability of resource users to engage in collective action in order to overcome the dilemmas associated with common-pool resource management in general (Gardner et al., 1990; Poteete et al., 2010), and regarding adaptive responses to droughts and other climatic disturbances in particular (Bisaro and Hinkel, 2016; Villamayor-Tomas, 2018). One important manifestation of collective action are members of WUAs participating in collective

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decision-making processes, for example, via participation in assemblies (Lopez-Gunn, 2003; Thuy et al., 2014; Valero de Palma, 2021). In such assemblies, community members decide collectively on current affairs as well as potential drought adaptation measures. Many adaptation measures have aimed at augmenting water supply by increasing storage capacity (e.g., dams or reservoirs) or developing new sources of water (e.g., exploiting groundwater, desalinizing saltwater, wastewater recycling, or transferring water)(Paneque, 2015). This focus shifted in the recent years towards an interest for demand-side management strategies (Llop and Ponce-Alifonso, 2012; Pereira et al., 2002; Sanchis Ibor et al., 2011) which reduce irrigation requirements by, e.g., improving efficiency or adapting cropping practices, although supply-side strategies, such as recycled or desalinated water, are continuously explored (Ballesteros-Olza et al., 2022; Martínez-Alvarez et al., 2023). The distinction between supply and demand measures can be traced back to early water and irrigation development studies and has been conceived as two different development paradigms. The supply paradigm was key throughout the 20th Century in semi-arid countries like Spain to mobilize state resources and build the necessary storage and conveyance infrastructure that would support irrigated agricultural expansion. The demand paradigm emerged later in the century, once most of the regulation infrastructure had been built, and structural water deficits started to emerge (Saurí and Del Moral, 2001).

The modernization of irrigation infrastructure is a demand side adaptation measure and has been promoted as such by the Spanish government in the last 25 years (RETEMA, 2025). Irrigation modernization usually implies replacing traditional furrow or flood systems (where water flows through channels between crop rows or floods the entire field) with drip or sprinkler technologies (which apply water directly to the root zone or spray it over crops, respectively) with the goal of increasing efficiency through a more precise application of available water. While water is potentially saved, no new water resources are created. Governments subsidizing these transformations frequently claim that they reduce water demand and entail ecological benefits (Berbel et al., 2019; Lopez-Gunn et al., 2012; Playán and Mateos, 2006; van der Kooij et al., 2015). As ample evidence suggests, these transformations frequently do not bring the desired results. First, realizing actual water savings for ecological purposes occurs only rarely and usually under accompanying policy interventions (Berbel et al., 2015; Schütze, 2025). There is indeed more evidence for cases where water consumption, the water used by the plants (evapotranspiration), increased after modernization than otherwise (Pérez-Blanco et al., 2020; Sampedro-Sánchez, 2022). This so-called irrigation rebound effect (Grafton et al., 2018; Perry et al., 2017) compromises the potential to improve agricultural drought resilience. Second, modernization has important institutional and managerial implications for collective irrigation systems (Ortega-Reig et al., 2017). Previous research has demonstrated how the introduction of new technologies permeates local collective irrigation management with unexpected outcomes, as for example, loss of autonomy in decision-making (Albizua and Zaga-Mendez, 2020; Poblador et al., 2021), increases in energy costs (Espinosa-Tasón et al., 2020; Rodriguez-Diaz et al., 2011), or changes in cropping patterns and allocation rules (Hoffmann and Villamayor-Tomas, 2023; Sese-Minguez et al., 2017). Despite these unintended negative drawbacks, irrigation modernization remains a major strategy in preparing the Spanish agricultural sector for future periods of drought (Gómez-Espín, 2019; RETEMA, 2025).

To assess how technological modernization can contribute to drought adaptation and performance, it is necessary to understand how it interacts with contextual conditions in which a system operates. There is not much knowledge, however, about what those conditions are. In this paper, we study some of the conditions under which micro-irrigation technology contributes to drought performance of Spanish WUAs.[1] We aim to answer the following research question: Under which institutional, social, and biophysical conditions does modernization contribute to drought performance of collective irrigation systems? To address this question, we compile a unique dataset containing technical and socio-institutional information of 61 Spanish WUAs and analyze it applying Qualitative Comparative Analysis. Specifically, we are interested in unveiling how modernization associates with factors such as number and type of drought adaptation measures, participation rates in collective decision-making processes, and availability of water sources in shaping satisfaction of water users with the key governance tasks of WUAs during droughts.

Our results show differences in the conditions that enable systems with different degrees of modernization to work well under drought conditions. Micro-irrigation dominated systems employ a relatively low number of adaptation measures to cope with droughts, most of which are supply-side oriented (e.g., drought wells, desalinated or recycled water). Alternatively, furrow-irrigation dominated systems employ mostly demand-side measures (e.g., changes in cropping patterns or allocation rules). In some cases, these systems also rely on a relatively high number of measures and on collective assembly decisions. Our findings challenge the narrative of modernization as an imperative necessity for drought adaptation, offer nuance to the dichotomy between demand- vs. supply-based solutions to water scarcity, and illustrate the interest of better understanding traditional irrigation in the current climate change context. Understanding such factors can guide the design of targeted and efficient strategies towards collective drought adaptation in irrigation.

2. Materials and Methods

2.1. *Qualitative Comparative Analysis*

Given our interest in exploring how modernization interacts with other contextual conditions, this study employs a Qualitative Comparative Analysis (QCA). QCA is a technique applicable to analyze empirical data based on set theory. It allows for causal interpretation of independent conditions in their conjoint effect (compared to inferring isolated effects via regression analysis) on an outcome condition and is particularly useful for analyzing small to medium n-sized datasets (Vis, 2012). Due to the nature of our data (see further below), we chose the crisp-set version of QCA (csQCA) for the analysis. Rooted in set theory and Boolean logic, cases are assigned to be either inside or outside of a set, which are, as put by Mahoney (2010:7, cited in Schneider and Wagemann, 2012), “boundaries that define zones of inclusion and exclusion”. Each case potentially belongs to many sets, depending on how many of the set’s characteristics can possibly be determined. It is the task of the researcher to conclude on the sets of interest for the analysis. Once the membership of the observed cases in each corresponding set has been established, the goal of the analysis is to identify which conditions (i.e., set memberships), or configurations thereof, are necessary or sufficient for the outcome of interest. Hence, this method specifically looks at configurations of conditions in their joint effect on an outcome, rather than their effect in isolation (Rihoux and Ragin, 2009; Schneider and Wagemann, 2012).

The analysis of sufficiency, the core analysis of QCA, unfolds by constructing a truth table. The truth table displays all theoretically possible combinations of conditions (2^k with k being the number of conditions) together with information on whether these combinations are represented by the cases. Unrepresented combinations are called logical remainders. Based on the truth table, the next step involves logical minimization, which aims at finding the simplest possible

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[1] Throughout this paper, we use the term water user association (WUA) to refer to irrigation communities (*comunidades de regantes* in Spanish).

expression associated with the outcome. Three types of solutions can be generated: the conservative (or complex), the parsimonious, and the intermediate solution. The conservative solution considers only those configurations of conditions for which the outcome is present and excludes logical remainders and contradictions. In contrast, the minimization algorithm for the parsimonious solution includes all logical remainders into the minimization process. Hence, it treats all logical remainders as if they were to produce the outcome, did they manifest in reality (Dusa, 2019). As implied by the name, the intermediate solution attempts to settle for a middle ground by including logical remainders that align with theoretical directional expectations and excluding logical remainders that consist of incoherent or untenable configurations.

In the past, QCA has received notable attention in the field of common-pool resource theory. For instance, Ragin et al. (2003) applied QCA to expand on Wade's (1989) analysis of factors for successful collective action in rural India. Lam and Ostrom (2010) study under which conditions improved irrigation infrastructure contributes to irrigation performance over time in Nepal, and Soliman et al. (2021) analyze the institutional performance of shared pumping systems as a form of collective action in Egyptian irrigation systems. QCA has further been applied to study the robustness of Ostrom's design principles for CBNRM (Baggio et al., 2016; Ma'Mun et al., 2020) and to study coordination in polycentric water governance systems (Pahl-Wostl and Knieper, 2023). Closest to our work, Villamayor-Tomas et al. (2020) investigate for the case of the WUAs in the "Riegos del Alto Aragón" project, how different paths or combinations of adaptation institutions contribute to successful drought adaptation in Spanish irrigation systems. Our study differs from Villamayor-Tomas et al. (2020) in the choice of our explanatory and outcome conditions. While Villamayor-Tomas et al. (2020) explain drought adaptation (measured through an irrigation performance index), our study explains community drought performance (measured by the satisfaction of water users with their community's functioning during droughts) using a different set of explanatory conditions. Additionally, our study relies on a country-wide sample.

2.2. Sample and data

In this study, we resort to two medium-sized datasets of survey data. The data were collected at the XIV and XV National Congresses of Spanish Water User Associations, which took place in 2018 and 2022, respectively. These quadrennial congresses are organized by FENACORE, the National Federation of Spanish WUAs. As of 2024, FENACORE comprises more than 350 associated WUAs with 700,000 members and two million hectares of land, representing more than 80% of irrigation in Spain (FENACORE, 2024). Throughout the duration of the two congresses, the data were collected via in-person surveys using pen and paper with participants of the congress (mainly representatives of Spanish WUAs[2]), who were selected quasi-randomly based on convenience sampling and with the goal to maximize sample size.[3] In total, 80 individuals completed the survey in 2018, and 63 in 2022. To our knowledge, approximately 100 WUAs tend to participate in these congresses. Thus, we managed to collect information on a relatively high proportion of WUAs in each congress. The final dataset used for the analysis counts 61 observations after eliminating missing values and duplicates. Hence, our sample represents approximately 17% of FENACORE-associated WUAs in Spain (median number of members 1100 and median irrigated area 3373 ha). The surveys encompassed topics such as WUA's responses to droughts, dynamics of water use and administration, irrigation related energy use, participation in social movements, and satisfaction with WUA management. The time required to complete the survey was approximately 15 min.

2.3. Selection of conditions

The two surveys were almost identical, and the identification of variables shared by both surveys was based on theoretical and practical considerations. Eventually, we selected six conditions for the analysis, which are described hereafter and summarized in Table 2. The corresponding survey questions can be found in Table A.1 in Appendix A.

2.3.1. SATISF - Performance as measured by satisfaction with WUA functioning

Our outcome condition is drought performance, which we operationalize as the WUA representatives' assessment of their members' satisfaction with key governance tasks during droughts. In the survey, each respondent was asked to assess the satisfaction of WUA members with respect to water allocation, infrastructure maintenance, the ability to acquire resources from other communities, and internal electricity management (if applicable), all during drought periods. The information on each aspect was measured on a 5-point Likert scale and overall satisfaction was calculated as the average of the scores attributed to each of the four aspects.[4] Although this measure reflects perceived rather than objective satisfaction, WUA representatives in Spain are in continuous exchange with members and we expected they have a strong capability in estimating and evaluating the overall stance within the WUA, especially in drought situations. Based on previous research, which has identified a strong relationship between user satisfaction and collective action (Kadirbeyoglu and Özertan, 2015; Naiga, 2021), we interpret this stated satisfaction as a measure of how well a WUA performs in its key tasks during droughts. In our measurement of satisfaction, we included several governance functions (water allocation, maintenance, ect.) in an attempt to capture both direct and indirect impacts of drought. Problems with water availability and allocation may trigger compliance with maintenance rules (Villamayor-Tomas and García-López, 2017) and/or disruptions in energy use and flows (Luque-Sánchez et al., 2025); the capacity to attract external resources, which is an important function regularly, becomes particularly salient during droughts.

2.3.2. MEAS - Number of collective drought adaptation measures

This condition counts the number of collective adaptation measures that the WUA typically organizes to cope with droughts. One possible interpretation of this condition is that the higher the number of adaptation measures available to a WUA, the higher the effectiveness in adapting to droughts and the more satisfied farmers are. On the contrary, many measures increase the cost of coordination and cooperation (Villamayor-Tomas, 2018), and could also indicate that a WUA faces challenges in identifying the most suitable approach to adapt and therefore needs to implement various instruments, while low numbers of measures might work well for other WUAs.

2.3.3. TECH - Degree of micro irrigation technology

This variable accounts for the degree of modernization, which is the presence of sprinkler or drip irrigation technology in a WUA. It therefore distinguishes between WUAs with high levels of furrow infrastructure and WUAs with mainly micro irrigation (sprinkler/drip) systems. It is also possible for a single WUA to consist of a combination of furrow and

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[2] It is normal that mainly WUA representatives are sent to such events, which limits the possibility to sample farmers without a mandate. However, a strength of this sample is that WUA representatives usually have the best knowledge on processes and decisions in the community and can estimate the average state of satisfaction within their community quite well.

[3] While we acknowledge that this is not a fully random sample of Spanish WUAs, it is quasi-random within the accessible population of congress participants.

[4] If a representative indicated that the WUA does not use electricity, the average score was calculated based on the first three managerial aspects, as the fourth did not apply.

micro systems. High levels of technification affect operation and maintenance of the irrigation system and pose additional cooperation and coordination challenges for farmers (Ortega-Reig et al., 2017; Poblador et al., 2021). To avoid confusion with WUAs that invest in these technologies (fully or partially) as a drought adaptation measure, we henceforth refer to WUAs that are already modernized (i.e., more than 50% of the system is sprinkler or drip) as "*micro-dominated*". In contrast, WUAs with a modernization rate of 50% or less will be referred to as "*furrow-dominated*".

2.3.4. DMAJ - Demand vs. supply measures

As outlined in the introduction, drought adaptation measures can be broadly aligned with the supply or demand paradigms (Pereira et al., 2002; Urquijo and De Stefano, 2016). As indicated by Pereira et al. (2002), supply measures aim at increasing the amount of water available, including increased storage capacity, or finding new water sources. Demand measures would include those that aim at reducing water requirements, i.e., via changes in cropping patterns and increases in efficiency or productivity. Thus, we created a binary condition indicating whether a WUA resorts to predominantly demand or supply measures (see Calibration), capturing the strategic orientation of drought responses. Table 1 presents how the measures were categorized into supply- and demand. Note that the measure "switching to drip or sprinkler irrigation" implies doing so as a response to drought and not necessarily to 100% drip or sprinkler. It is thus possible that WUAs are still classified as "furrow-dominated" if they modernize only a fraction of their area or that WUAs that are "micro-dominated" can further increase their proportion of micro-irrigation. Also importantly, defining what involves increases in water availability vs. reductions in demand varies with scale. Pereira et al. (2002) classify storage and conveyance improvements as supply-based measures; however, we understand they do so because they consider those measures as being implemented outside the irrigation system (so more water indeed reaches the system). However, we classified those as demand-based because, in our context, they are implemented within the system by the WUAs with the goal of reducing water losses once the water enters the system. The same applies to water exchanges; while external water exchanges could be considered a supply measure, we considered exchanges within the community as a demand measure because the goal is to increase water productivity.

2.3.5. ASIST - Assistance to assemblies

Collective decision-making in WUAs usually takes place during assemblies, to which all members are invited (and expected) to participate. The primary purpose of these assemblies is to allow farmers to decide upon and control the activities of the WUA and raise important topics and pressing issues regarding current developments (Valero de Palma, 2021). The rate of participation in the assemblies is therefore a point of reference for community engagement and involvement. Especially during droughts, high participation can potentially indicate two scenarios. On the one hand, higher participation could have a positive impact on satisfaction, if it allows the community to better resolve pressing issues. On the other hand, high participation could also be a sign of low satisfaction with matters, motivating farmers that usually abstain from assemblies to show up. In the survey, we asked representatives whether the attendance at assemblies increases, decreases, or does not change during droughts, i.e., whether droughts are an incentive for higher rates of collective action.

Table 1
List of supply and demand measures included in the survey.

Supply	Demand		
River water pumping	Leaving land uncultivated	Canal improvement	Changes in water allocation
Utilization of "drought wells" (*pozos de sequia*)	Reduction of high-water consuming crop	Ground levelling	Water exchanges within the community
Utilization of desalinated water	Introduction of new crop	Regulatory pool construction	
Utilization of recycled/treated water	Restricting more than one harvest per year	Switching to drip or sprinkler irrigation	

2.3.6. FUENTE - Availability of water sources

Finally, the capacity of WUAs to adapt to drought periods also depends on how many sources of water are at their disposal. The availability of multiple sources of water provides the community with alternatives, in case of supply shortages of one source, which increases their adaptive capacity, but can also influence related water costs (Urquijo and De Stefano, 2016).

2.4. Calibration

Although there are some drawbacks associated with the use of crisp sets, for example the loss of information as a result of dichotomization or more sensitivity with regards to the decisions made by the researcher (Schneider and Wagemann, 2012; Skaaning, 2011), we chose csQCA for three reasons. First, two of the selected variables for the analysis are binary by nature, reducing the potential loss of empirical information from dichotomization. Second, Rihoux (2006) contends that dichotomized data are the preferred approach for small and medium-n analyses when working with case-based knowledge as opposed to other techniques. This aligns with the conditions of our study. Third, the application of QCA, including the minimization process and the interpretation of results, is comparatively easier and more straightforward to understand using crisp instead of multi-value or fuzzy sets.

CsQCA implies calibrating non-binary variables into a dichotomized version, i.e., assigning them for each case to be either inside or outside the corresponding set. For the four non-binary variables, we first visualized their distribution (see Figure B1 in Appendix B) and set the calibration threshold according to context-dependent considerations. Table 2 summarizes the selected conditions and how they were calibrated. For example, if a case has an average satisfaction score of 3 or

Table 2
Description and crisp calibration of the outcome and explanatory conditions.

Condition	Description	Calibration value	
		0 if	**1 if**
SATISF	Satisfaction calculated as the average satisfaction score from 4 (or 3) Likert-score responses	2.9 or less on the average satisfaction score (~SATISF)	3 or more on the average satisfaction score (SATISF)
MEAS	Number of collective drought adaptation measures executed by the WUA	3 or less collective measures (~MEAS)	4 or more collective measures (MEAS)
DMAJ	Indicates whether demand or supply measures dominate WUA responses to drought	more supply than demand measures or tied (~DMAJ)	more demand than supply measures (DMAJ)
ASIST	Indicates whether the assistance to assemblies changes during droughts	assistance decreased or remained unchanged (~ASIST)	assistance increased (ASIST)
TECH	Degree of modernization of the WUA	50% or more of the irrigation system are furrow/gravity systems (~TECH)	more than 50% of the irrigation system are micro-irrigation systems (TECH)
FUENTE	Number of water sources available to the WUA	only one water source available (~FUENTE)	more than one water source available (FUENTE)

higher, it is assumed to be inside the set of cases with high satisfaction (SATISF, calibration value = 1). This is also referred to as empirical presence of the condition. Conversely, if a case has an average satisfaction score lower than 3, it is considered to be outside the set of cases with high satisfaction, hence, characterized by low satisfaction (~SATISF, calibration value = 0). This is referred to as empirical absence of the condition. This logic applies equally to all conditions. The result of the calibration process yields the calibrated data matrix. A detailed description of the calibration process and the corresponding tables and figures are presented in Appendix B. This calibrated data matrix is the basis for the subsequently presented analyses of necessity and sufficiency, which were conducted using version 3.18 of the “QCA” package (Dusa, 2019) in R Version 4.2.1 (R Core Team, 2022).

3. Results

In the following, we present the results of the analysis for the combined dataset for the years 2018 and 2022. For completeness, we present the same analysis for the two years separately in Appendix D. Similarly, Appendix E reports on the analysis of the absence of outcome.

3.1. Analysis of necessity

The analysis of necessity for each condition and both the presence and absence of the outcome is presented in Table 3. In order to be accounted for as necessary, consensus among QCA scholars recommends consistency scores to be at least 0.9 (Ragin, 2006). As the scores in Table 3 show, the condition DMAJ reaches a consistency score of 0.944 for the absence of the outcome condition. Hence, employing a majority of demand-side measures is a necessary condition for low satisfaction with WUA performance during droughts. At the same time, its coverage is relatively low (0.347), indicating that DMAJ and ~SATISF appear together only in 34.7% of the occurrences of DMAJ, making DMAJ a rather irrelevant necessary condition. The same condition, however, reaches a consistency score of 0.744 and a coverage of 0.653 for the presence of the outcome.

3.2. Analysis of sufficiency

In the following, we report on the conservative (or complex) solution as it makes no assumptions about logical remainders. For completeness, the (enhanced) parsimonious and intermediate solutions are shown and commented on in Appendix C. The mapping of case numbers to actual WUA names is shown in Table F.1 in Appendix F. Given the resulting truth table (B.3 in Appendix B), the minimization yields an overall inclusion score of 0.886 and a coverage score of 0.721 for the solution formula, while consisting of seven configurations that cover 31 cases (excluding the four contradictory cases 43, 15, 50, and 55). Each configuration is sufficient to produce the outcome and consists of several conditions in conjunction (i.e., the joint occurrence of the conditions, present or absent). Those conditions that do not appear in a configuration are irrelevant in the sense that they can either be absent or present without affecting the outcome. The single configurations that lead to the outcome, each representing one solution, are displayed in Table 4. Coverage scores for the individual solutions range from 0.186 (i.e., 18.6% of the cases with present outcome are covered by the solution) to 0.047.

To account for relevance, we focus the description and discussion of results only on those solution configurations that cover at least 5 cases or have a coverage above 10%, hence on solution terms 1–4, which encompass 22 WUAs.

The first solution combines the absence of MEAS and FUENTE with the presence of TECH. Thus, the cases covered by this configuration are micro-dominated WUAs that, during droughts, do not carry out more than three collective drought adaptation measures and that count on one sole source of water. This configuration contains two contradictory cases (inclS = 0.8) but covers 18.6% of the cases with high satisfaction present. Solution configuration 2 contains the absence of MEAS, ASIST, and TECH, and the presence of DMAJ. This describes the drought performance of furrow-dominated WUAs, which rely primarily on a low number of demand-side oriented adaptation measures and exhibit a low to normal rate of participation to assemblies during droughts. This configuration includes one contradictory case (inclS = 0.875) and covers 16.3% of the cases with present outcome. Configurations 1 and 2 have the highest coverage scores within the complete solution. The third configuration consists of the absence of conditions MEAS and DMAJ, but the presence of TECH. This is reflected in the situation of 5 micro-dominated WUAs that implement no more than three collective measures, which are rather supply-side oriented. This solution covers 11.6% of drought resilient communities and does not include contradictory cases (inclS = 1). Finally, solution 4 also covers 11.6% of cases with the outcome present and includes the presence of MEAS, DMAJ, ASIST and the absence TECH. Hence, it comprises furrow-dominated WUAs that apply more than three measures, which are by majority demand-oriented, and that experience an increased participation to assemblies during droughts.

A more detailed examination of the measures reported by the WUAs reveals the number and types that both micro and furrow systems from the main solution configurations have reported to employ (Table 5). We divide the demand-side measures into three categories: cropping strategies, institutional change, and infrastructure improvements. Cropping

Table 3
Consistency and coverage scores from the analysis of necessity. A tilde (~) in front of a condition indicates its absence.

	Presence of outcome (SATISF)		Absence of outcome (~SATISF)	
Condition	*Consistency (inclN)*	*Coverage (covN)*	*Consistency (inclN)*	*Coverage (covN)*
MEAS	0.442	0.633	0.611	0.367
DMAJ	0.744	0.653	**0.944**	0.347
ASIST	0.535	0.657	0.667	0.343
TECH	0.488	0.677	0.556	0.323
FUENTE	0.256	0.733	0.222	0.267
~MEAS	0.558	0.774	0.389	0.226
~DMAJ	0.256	0.917	0.056	0.083
~ASIST	0.465	0.769	0.333	0.231
~TECH	0.512	0.733	0.444	0.267
~FUENTE	0.744	0.696	0.778	0.304

Table 4
Results from the analysis of sufficiency (conservative solution). Each row represents one sufficient configuration for the outcome SATISF, where the asterisk (*) indicates a logical AND. Inclusion indicates how reliably a configuration leads to the outcome (i.e., the extent to which the configuration is a subset of the outcome). Coverage indicates the empirical relevance of the configuration (i.e., the proportion of the outcome it explains). A tilde (~) in front of a condition indicates its empirical absence. Points (•) behind cases mark contradictory cases (cases that would be expected to include the satisfaction outcome but do not).

	Configuration	Inclusion	Coverage	Cases (WUA)
1	~MEAS*TECH*~FUENTE	0.8	0.186	33, 58, 10, 18, 43•, 60, 1, 15•, 17, 56
2	~MEAS*DMAJ*~ASIST*~TECH	0.875	0.163	3, 5, 7, 48, 50•, 57, 30, 54
3	~MEAS*~DMAJ*TECH	1	0.116	33, 25, 58, 16, 21
4	MEAS*DMAJ*ASIST*~TECH	0.833	0.116	27, 36, 46, 53, 55•, 26
5	MEAS*~DMAJ*ASIST*FUENTE	1	0.07	11, 32, 52
6	~DMAJ*~ASIST*~TECH*~FUENTE	1	0.07	2, 4, 13
7	MEAS*DMAJ*~ASIST*TECH	1	0.047	31, 12

Table 5
Distribution of adaptation measures between micro- and furrow dominated systems. Micro-dominated systems are represented by configurations 1 and 3 (11 cases), furrow-dominated systems are represented by configurations 2 and 4 (12 cases).

	Micro-dominated systems (Config. 1 and 3)	Furrow-dominated systems (Config. 2 and 4)
Supply-side measures		
River pumping	0	0
Drought wells	2	4
Use of desalinated water	3	0
Use of recycled/treated water	2	0
TOTAL	7	4
Demand-side measures		
Cropping strategies		
Leaving land uncultivated	2	4
Reducing high-water consuming crop	1	7
Introduction of new cropping varieties	0	0
Restricting more than one harvest per year	0	2
Institutional change		
Changes in water allocation	7	7
Water exchanges within the community	1	2
Infrastructure improvements		
Canal improvement	0	5
Ground levelling	0	1
Regulatory pool construction	1	3
Sprinkler or drip installation	6	4
TOTAL	18	33

strategies include leaving parts of the land uncultivated, switching to less water-consuming crops, or restricting the number of harvests per year. Institutional change strategies refer to drought-related alterations of the rules-in-use, such as allocation turns and water exchanges within the community (internal water markets). Infrastructure improvements aim at increasing the efficiency of water use or conveyance by improving canals, levelling ground, installing sprinkler or drip irrigation, or constructing regulatory pools to regulate water flow. As confirmed in Table 5, micro-dominated systems rely relatively more on supply than demand-side measures overall, while the opposite is true for furrow-dominated systems. Within the demand-side measures, those related to institutional change are the only ones that remain relatively balanced across the two WUA types.

Looking at the geographical distribution of the communities represented by each solution, we find that the results are spatially robust since, except for one configuration, there is no clear pattern after which the WUAs cluster according to their location (Fig. 1). The exception are WUAs grouping in solution configuration 3 (green dots in Fig. 1) which scatter particularly around the East of Spain. Hence, in our sample, particularly eastern WUAs characterize as having a high degree of micro-irrigation and with a low number of drought adaptation measures, which are mainly supply-oriented.

4. Discussion

The results allow us to observe some interesting patterns. First, we find that both WUAs dominated by micro as well as furrow irrigation appear in the four major solutions with high satisfaction. This means that neither type inherently leads to higher satisfaction than the other during droughts. In other words, and contrary to mainstream governmental agendas, our study shows that furrow-dominated/traditional irrigation does not underperform during droughts as compared to micro-dominated/modern irrigation (Berbel et al., 2019). Our distinction between micro and furrow-oriented irrigation positions around the differentiation of "modern" vs. "traditional" irrigation and related debates around their resilience (Aubriot, 2022; Ertsen, 2002; Leibundgut and Kohn, 2014; Sengupta, 1938). More importantly, the result also illustrates the importance of enriching the traditional vs. modern irrigation debate by looking more broadly at the diversity of technological, biophysical, social, and institutional conditions that explain drought adaptation in irrigation systems (Cox, 2014; de Bont et al., 2019; van Rooyen et al., 2020; Villamayor-Tomas et al., 2020). Villamayor-Tomas et al. (2020), for example, illustrate how the traditional vs. modern irrigation distinction (coined as Asian vs. American irrigation types) needs qualification in light of a variety of aspects that range from the levels of technification to the formalization of management rules, social capital, or professionalization. This finding is also relevant to policymaking, providing evidence for policies to move beyond a singular focus on technological upgrades and instead supporting diverse pathways to high performance during drought, including strengthening local governance and collective action.

Second, our findings qualify the promotion of demand-side measures as the only means to increase the performance of irrigation systems in the climate change context. While the water demand management

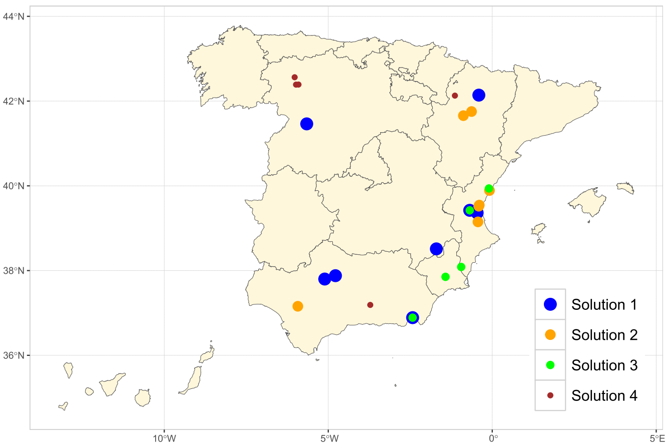

Fig. 1.. Geographical location of the WUAs covered by each solution within Spain. The size of the dots decreases with the coverage of the solutions to visualize overlaps. The map was created using the "mapSpain" R package, version 0.8.0 (Hernangómez, 2023). Reference to Fig. 1 caption. Hernangómez, D. (2023). *mapSpain: Administrative Boundaries of Spain*. https://doi.org/10.5281/zenodo.5366622.

paradigm has historically included both technological and social (i.e., institutional) solutions, governments have predominantly focused on the former as a way to cope with climate change and droughts. As we find, there is no linear relationship between "modern" technologies aiming at increasing efficiency and performance, nor a clear-cut division between supply and demand strategies. The relative dominance of micro-irrigation, a paradigmatic demand-side technological solution, can mediate the suitability of other demand-side measures. Micro-irrigation systems can reach theoretical efficiencies of up to 95% (van der Kooij et al., 2013), which makes obtaining new efficiencies particularly difficult as compared to less efficient systems. This is why micro-dominated systems may resort less frequently to demand-side strategies than furrow-dominated systems. Also, relying on new sources of water or intensifying the use of existing ones (like groundwater) can have negative impacts in systems where investments in new technologies have been driven by the goal of increasing productivity (Berbel et al., 2019; Hoffmann and Villamayor-Tomas, 2023; Lopez-Gunn et al., 2012) and satisfying global food markets (Akram-Lodhi, 2017). As shown elsewhere, development trajectories driven by technological improvements and productivity maximization can also reduce a system's adaptability to social, political, or biophysical changes (Anderies et al., 2006).

The micro-irrigation dominated systems represented in configurations 1 and 3 are also characterized by resorting to a comparatively small number of measures (i.e., absence of MEAS). One potential explanation for this is that having a micro-dominated irrigation system would reduce the need for other drought adaptation measures during droughts, suggesting a successful contribution of modernization programs to drought adaptation on the community-level (Berbel et al., 2019). Conversely, modern irrigation technologies can lock farmers into a specific way of managing water, for example, due to infrastructural rigidity, reducing room for adaptation or innovation. Also, the lower number of measures could be associated with the rise of centralization. Modernization has justified the centralization of management in some contexts, including the hiring of new, specialized professionals (Poblador et al., 2021; Sanchis-Ibor et al., 2017). This centralization can, in turn, crowd out the initiative of farmers to e.g., cope with droughts via collective measures (Garrick, 2018). Interesting is also the concentration of WUAs in configuration 3 at the Eastern coast of Spain, which could potentially be explained by the domination of export-oriented commercial agriculture in the area.

Furrow-dominated systems characterized by solution configurations 2 and 4 depict a different scenario. WUAs in both configurations resort primarily to demand rather than supply-side measures (Table 5) but differ in terms of the assistance to assemblies and the number of drought adaptation measures. They either employ few measures and do not experience an increase in assistance to assemblies (configuration 2) or they do implement many measures and observe an increase in assistance to assemblies (configuration 4). We ascribe this observation to the possibility that a higher number of measures requires a high degree of coordination effort and participation (Villamayor-Tomas, 2018). Alternatively, it is also possible that the higher number of measures reflects struggles to cope with droughts and therefore conflicts, which would, in turn, justify enhanced communication among farmers (i.e., via assemblies). Our findings also show that implementing many adaptation measures is not necessarily conducive to better drought performance. On the one hand, a greater number and variety of measures should provide for abundance in reacting to droughts (Urquijo and De Stefano, 2016). On the other hand, larger numbers of measures also involve higher transaction costs, particularly in the context of collective irrigation management (Villamayor-Tomas, 2018). Our findings tend to support the latter conjecture as three of the four main solution configurations include WUAs with few adaptation measures.

Finally, although appearing as a condition in configuration 1, the interpretation of the FUENTE condition is ambiguous. At first glance, water supply diversity should increase drought performance. Our major solution terms, however, include only the absence of the FUENTE condition (i.e., WUAs disposing of only one source of water). We attribute this to two potential reasons. First, more sources can lead to higher water costs (e.g., due to higher energy consumption for pumping groundwater, treatment expenses for recycled water, or fees for water transfers) (Urquijo and De Stefano, 2016), impacting drought performance negatively. Second, having access to more than one source of water might discourage additional drought adaptation measures, leaving those WUAs more vulnerable to possible failures in the supply of their existing sources, increasing effort to respond to such additional vulnerabilities. Alternatively, based on our data, it could be due to the skewed distribution of the condition, as almost 75% of the WUAs reported having only one source at their disposal. It also shows that having "only" one source of water does not constitute a problem for WUAs to cope with droughts, and our results demonstrate some of the conditions, under which WUAs with only one source can reach high satisfaction.

4.1. Limitations and future research

Although our study is a first step into identifying contextual conditions around modernization conducive to satisfaction with water governance during droughts, the results are far from conclusive. There is an almost uncountable number of contextual conditions which potentially influence the success of collective action for drought adaptation (Agrawal, 2001; Wang and Chen, 2021). Our study covers only a small number of relevant conditions that we had data on, given the difficulties of collecting survey data from WUAs due to the resistance of WUA representatives to either fill the surveys or share certain types of data. Future research shall focus on collecting data from WUAs that are most willing to collaborate and share information. Such information could further include physical (e.g., water consumption), institutional (e.g., water allocation mechanisms, monitoring rules), socio-economic (e.g., WUA income), or cognitive (e.g., mental frames and perceptions) data. Evidently, this listing is far from exhaustive, and researchers should select conditions based on availability and practical relevance in the context of their study. Furthermore, and particularly relevant for future applications of QCA, researchers should collaborate closer with WUAs to extract more qualitative information that can better inform the solutions generated by the analysis. In our case, we have very limited possibilities to "go back to the cases" to verify or cross-check the results because the variables were reported through a survey and are either perception-based or not externally verifiable. Future research in this direction should consider more profound data collection and rely on more concrete variables. Solutions from such analyses can be reported back to the WUAs involved, giving them the possibility to discuss the solutions in general assemblies, potentially enhancing informed decision-making and collective learning. Although our study aimed at illustrating the results with qualitative insights, survey data is limited in its possibility to provide it. Alternative methods, e.g., focus groups or participatory research practices, could increase the richness of qualitative data and therefore of the results of QCA. We also acknowledge that our sampling was not purely random. This might raise questions about generalizability and representation of our sample regarding the entirety of WUAs in Spain. Although the mapping of the major solution cases did not show spatial concentration, future efforts could attempt different ways of data collection. Finally, we want to emphasize that our understanding of drought performance in the context of this study is imperfect and limited to the community-level. Given the difficulty in measuring drought performance objectively, we resorted to a proxy based on the representative's assessment of member satisfaction with key governance tasks during drought. Although we believe that WUA representatives are in a good position to estimate how members perceive performance, this measure may not necessarily reflect the general or relative effectiveness of drought adaptation, and our results need to be interpreted considering the imperfect nature of this measure. Also, as our focus was centered around local-level drought responses at the community-level, our results may not necessarily be transferable to larger scales, as e.g., to the basin-level. A more holistic approach to understanding adaptation to and performance during drought on a larger scale will certainly encompass governance and policymaking across WUAs (Bressers et al., 2016).

5. Conclusion

The aim of this study was to identify configurations of conditions that contribute to successful drought performance of WUAs, as measured by the satisfaction of WUA members with key governance tasks during droughts. To this end, we applied a crisp-set QCA on national-level survey data from Spain. Our results advance existing knowledge in various directions. WUAs with a high proportion of drip- or sprinkler irrigation in our sample report higher levels of satisfaction when this is combined with supply-side drought adaptation measures. While these strategies may offer short-term relief, they can also put a system's ecological sustainability into question. Moreover, as efficiency gains in already modernized WUAs face diminishing returns, improving efficiency even further is challenging to attain. Furrow-dominated or "traditional" WUAs do not encounter these issues. Those WUAs in our sample report satisfaction during drought when they practice combinations of demand-side measures. Compared to modern ones, traditional WUAs can resort to various efficiency-increasing demand-side measures more easily (as efficiency increases are more easily achievable). This shows that modernization is not the only solution to drought adaptation for furrow-dominated irrigation systems. While modernization can indeed contribute to drought adaptation, our findings highlight that WUAs are also capable of adapting effectively through alternative strategies. Moving forward, policymaking should consider the distinct responses of "traditional" and "modern" WUAs. Targeted policy interventions could encourage different strategies and objectives for each type of WUA, enhancing the potential for successful drought adaptation.

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CRediT authorship contribution statement

Sergio Villamayor-Tomas: Writing – review & editing, Validation, Supervision, Conceptualization. **Patrick Hoffmann:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors declare that no generative AI or AI-assisted technologies were used in the process of writing this manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendices

A. *Survey questions for selected conditions*

Table A.1
Survey questions for selected conditions

Condition	Survey question (Spanish - *original*)	Survey question (English - *translated*)
SATISF (OUTCOME)	¿Del 1 al 5 cuán satisfecho cree que los regantes de su comunidad están con los siguientes aspectos relativos a la administración de la comunidad? (1 = muy insatisfechos, 5 = muy satisfechos). Marcar NA si no aplica. ● Reparto de agua ● Conservación de la infraestructura ● Conseguir recursos de otras entidades ● Gestión de la electricidad	From 1–5 how satisfied do you think the irrigators in your community are with the following aspects related to the administration of the community (1 = very dissatisfied, 5 = very satisfied). Mark NA if not applicable. ● Water distribution ● Infrastructure maintenance ● Obtaining resources from other entities ● Electricity management
MEAS	¿Qué medidas de las de más abajo *ha organizado la comunidad de regantes* para hacer frente a las sequías? Marque con una X todas las que apliquen. [Listado de medidas]	Which of the measures below has the irrigation community organized to cope with droughts? Mark with an X all that apply. [List of measures]
TECH	¿Qué porcentaje de la superficie de su comunidad se riega por…? ● Inundación ● Aspersión ● Goteo (Nota: tiene que sumar 100%)	What percentage of your community's surface area is irrigated by…? ● Furrow ● Sprinkler ● Drip (Note: must add up to 100%)
DMAJ	-	-
ASIST	¿Durante sequías, cambia el número de miembros que asisten a las asambleas?	During droughts, does the number of members attending assemblies change?
FUENTE	¿Qué fuentes de agua utiliza su comunidad durante años de disponibilidad normal de agua?	What water sources does your community use during years of normal water availability?

B. Calibration process and rationale

Table B.1
Raw data matrix

ID	WUA	SATISF	ASIST	TECH	FUENTE	MEAS	DMAJ
1	Tamarite La Concepcion	3,3	1	65	1	3	1
2	Junta de Acendados de la Huerta de Murcia	3	0	0	1	3	0
3	Villamayor	3	0	0	1	2	1
4	Canal de Castellon	3,3	0	0	1	2	0
5	Alzira	4	0	50	1	3	1
6	Sector IV	3,8	1	100	1	4	1
7	Burjasot, Godella y Rocafort	3,3	0	0	1	3	1
8	Colectividad Puente Genil	2	1	100	1	4	1
9	Benferri	2,5	0	100	2	3	1
10	Sectores X y XI	5	0	100	1	3	1
11	Acequia de tormos	3	1	0	2	5	0
12	Palazote la Herrera	4	0	100	2	5	1
13	Favara	3	0	0	1	6	0
14	Acequia Arabuelia	2	0	10	1	6	1
15	Zairin	2,2	1	85	1	3	1
16	San Onofre Torromendo	3,5	1	100	4	3	0
17	Canal de la margen izquierda del Genil	4,8	1	80	1	3	1
18	Juan Partinez Parras	4	0	100	1	3	1
19	Llanos de Camarera	2,7	0	10	1	11	1
20	CG Regantes del Canal del Paramo de Leon	4	1	80	1	4	1
21	CR de Alhama de Murcia	3,3	1	80	2	3	0
22	Margen Derecha Segura	2,8	0	50	5	4	0
23	CR Godolleta	1,8	1	100	1	4	1
24	Sindicato de Riegos Canal de Tauste	2,7	1	5	2	3	1
25	Canal de la Cota 100 Margen derecho del rio Mijos	4,5	0	70	2	1	0
26	CG Bardenas	3,3	1	28	2	5	1
27	SC Embalse Villameca	3,3	1	40	1	4	1
28	Benacher y Faitanar	2,8	1	60	1	5	1
29	Canal Imperial Aragon	4,5	1	0	1	2	1
30	CR Bajo Guadalquivir	4	0	50	2	2	1
31	CR Casinos	4,7	0	100	1	5	1
32	CR Tajo Segura Librilla	5	1	25	2	6	0
33	Cuatro Vegas Almeria	4	0	100	1	1	0
34	CR de Guadiana	3,5	1	100	1	7	1
35	CUAS Mancha Occidental II	1,5	1	100	1	7	1
36	CR Ciudad de Santa Fe	3,8	1	40	1	4	1
37	CR Montijo	4	1	75	1	5	1
38	Santa Maria del Paramo Alto	3,2	1	85	1	4	1
39	Sector Nr. 5	3	1	25	1	3	1
40	Canal de Castañon	2	1	10	1	2	1
41	Presa Cerrajera	2,8	1	65	1	6	1
42	CR Sector 2 Los Tollos	4,8	0	100	2	2	1
43	CR del Paramo Alto	2,5	0	80	1	3	1
44	CR Pantano del Rumblar	2	1	40	1	2	1
45	Sector Nr. 3	4	0	0	1	6	1
46	CR del Canal alto de Villares	4,7	1	30	1	5	1
47	Sindicato de Riegos de Soller	3,2	1	60	1	4	1
48	Sindicato de Riegos de Rabal	3,7	0	0	1	3	1
49	CR El Ferial	1,5	1	100	1	5	1
50	CR Urdan (CR Nuez de Ebro)	1,5	0	0	1	2	1
51	CR Presa de la Manga	2	1	70	2	5	1
52	CR Totana	3,5	1	92	3	5	0
53	CR de Tres Consejo	4,7	1	30	1	5	1
54	Real Acequia Moncada	4	0	0	2	3	1
55	CR Presa de la Vega de Abajo	1	1	30	1	4	1
56	CR de la Margen Izquierda del Rio Bembezar	4	1	100	1	3	1
57	CR de Burriana	3,7	0	2	1	3	1
58	CR San Pedro Apostol de Godilleta	4,5	1	100	1	2	0
59	CR Villadangos del Paramo	3,7	0	10	1	6	1
60	CR La Virgen del Aviso	5	0	100	1	2	1
61	CR Losa del Obispo	3,3	1	5	1	2	1

The conditions DMAJ and ASIST are binary by nature and therefore do not require calibration. The calibration of the remaining variables into binary form was based on their visualizations (see Figure B.1) and theoretical considerations. The rationale behind each selected threshold is briefly explained in the following.

SATISF: The average satisfaction score over the governance-related aspects ranges from 1 to 5. Overall satisfaction on average was higher than the arithmetic mean of 2.5. We therefore opted for a cutoff value of 3, i.e., a score of 3 or more accounts for the presence of satisfaction, and a score below 3 for the absence of satisfaction. This is justified based on the distribution of the data points, ensuring variation in the dataset, and based on the consideration that 3 is the neutral value on a 5-point Likert scale, suggesting that scores below 3 typically represent dissatisfaction, and values above 3 represent satisfaction.

MEAS: The cutoff value for what counts as “many” and “few” adaptation measures is difficult to justify by theory. Therefore, we opted for a value that splits the dataset into approximately equal parts to allow for variation. Although this choice might not be generalized to other cases, it does represent well what “many” and “few” mean relative to our dataset.

TECH: It is reasonable to assume that an irrigation system can be called modernized, if at least the majority of its infrastructure has been converted to drip and/or sprinkler irrigation. Therefore, the threshold for modernized irrigation systems has been set to 51%, meaning that if at least 51% of the irrigation is done via sprinkler and drip irrigation, the case belongs to the modernized irrigation systems. On the other hand, at least 50% of irrigation being traditional furrow irrigation means absence of modernization. This also aligns well with the distribution of the data.

FUENTE: The scope of choosing a threshold for the number of water sources is quite limited, as the clear majority of the included cases only dispose of one source. Therefore, we count only one source of water supply as the absence of a diversity of water sources, and more than one source as the presence of a diversity of water sources.

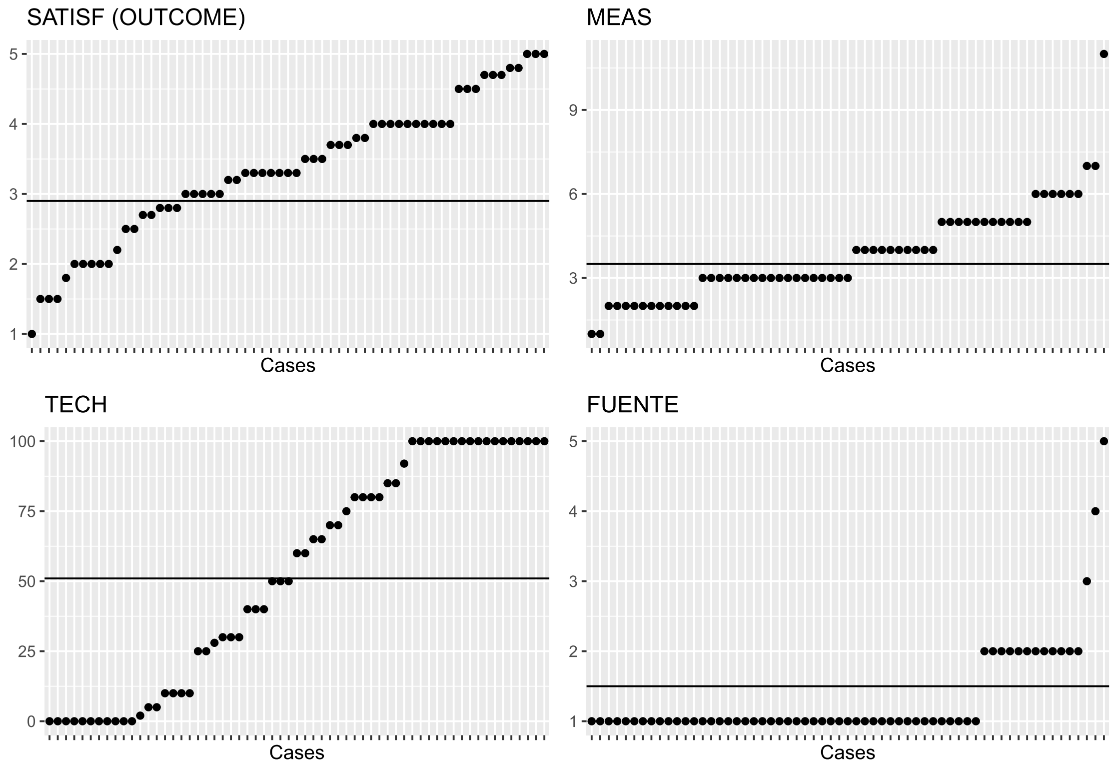

Figure B1. Visualization of calibration thresholds

Table B.2
Calibrated data matrix

ID	WUA	SATISF	ASIST	TECH	FUENTE	MEAS	DMAJ
1	Tamarite La Concepcion	1	1	1	0	0	1
2	Junta de Acendados de la Huerta de Murcia	1	0	0	0	0	0
3	Villamayor	1	0	0	0	0	1
4	Canal de Castellon	1	0	0	0	0	0
5	Alzira	1	0	0	0	0	1
6	Sector IV	1	1	1	0	1	1
7	Burjasot, Godella y Rocafort	1	0	0	0	0	1
8	Colectividad Puente Genil	0	1	1	0	1	1
9	Benferri	0	0	1	1	0	1
10	Sectores X y XI	1	0	1	0	0	1
11	Acequia de tormos	1	1	0	1	1	0
12	Palazote la Herrera	1	0	1	1	1	1
13	Favara	1	0	0	0	1	0
14	Acequia Arabuelia	0	0	0	0	1	1
15	Zairin	0	1	1	0	0	1
16	San Onofre Torromendo	1	1	1	1	0	0
17	Canal de la margen izquierda del Genil	1	1	1	0	0	1
18	Juan Partinez Parras	1	0	1	0	0	1
19	Llanos de Camarera	0	0	0	0	1	1
20	CG Regantes del Canal del Paramo de Leon	1	1	1	0	1	1
21	CR de Alhama de Murcia	1	1	1	1	0	0

(*continued on next page*)

Table B.2 (*continued*)

ID	WUA	SATISF	ASIST	TECH	FUENTE	MEAS	DMAJ
22	Margen Derecha Segura	0	0	0	1	1	0
23	CR Godolleta	0	1	1	0	1	1
24	Sindicato de Riegos Canal de Tauste	0	1	0	1	0	1
25	Canal de la Cota 100 Margen derecho del rio Mijos	1	0	1	1	0	0
26	CG Bardenas	1	1	0	1	1	1
27	SC Embalse Villameca	1	1	0	0	1	1
28	Benacher y Faitanar	0	1	1	0	1	1
29	Canal Imperial Aragon	1	1	0	0	0	1
30	CR Bajo Guadalquivir	1	0	0	1	0	1
31	CR Casinos	1	0	1	0	1	1
32	CR Tajo Segura Librilla	1	1	0	1	1	0
33	Cuatro Vegas Almeria	1	0	1	0	0	0
34	CR de Guadiana	1	1	1	0	1	1
35	CUAS Mancha Occidental II	0	1	1	0	1	1
36	CR Ciudad de Santa Fe	1	1	0	0	1	1
37	CR Montijo	1	1	1	0	1	1
38	Santa Maria del Paramo Alto	1	1	1	0	1	1
39	Sector Nr. 5	1	1	0	0	0	1
40	Canal de Castañon	0	1	0	0	0	1
41	Presa Cerrajera	0	1	1	0	1	1
42	CR Sector 2 Los Tollos	1	0	1	1	0	1
43	CR del Paramo Alto	0	0	1	0	0	1
44	CR Pantano del Rumblar	0	1	0	0	0	1
45	Sector Nr. 3	1	0	0	0	1	1
46	CR del Canal alto de Villares	1	1	0	0	1	1
47	Sindicato de Riegos de Soller	1	1	1	0	1	1
48	Sindicato de Riegos de Rabal	1	0	0	0	0	1
49	CR El Ferial	0	1	1	0	1	1
50	CR Urdan (CR Nuez de Ebro)	0	0	0	0	0	1
51	CR Presa de la Manga	0	1	1	1	1	1
52	CR Totana	1	1	1	1	1	0
53	CR de Tres Consejo	1	1	0	0	1	1
54	Real Acequia Moncada	1	0	0	1	0	1
55	CR Presa de la Vega de Abajo	0	1	0	0	1	1
56	CR de la Margen Izquierda del Rio Bembezar	1	1	1	0	0	1
57	CR de Burriana	1	0	0	0	0	1
58	CR San Pedro Apostol de Godilleta	1	1	1	0	0	0
59	CR Villadangos del Paramo	1	0	0	0	1	1
60	CR La Virgen del Aviso	1	0	1	0	0	1
61	CR Losa del Obispo	1	1	0	0	0	1

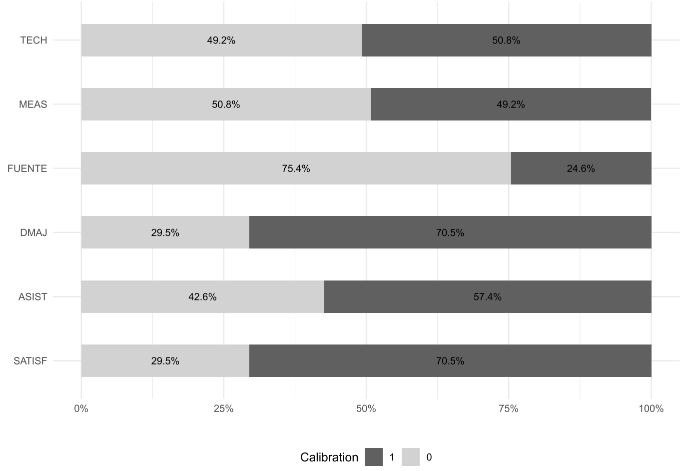

Figure B2. Size of the crisp-sets

The truth table (Table B.3) shows how the 61 observations group into 23 rows (the 9 logical remainders are omitted from the table). 15 out of the 23 configurations found in our data are unambiguous, while 8 constitute potential contradictions, i.e., they can equally lead to the presence and the absence of an outcome. Rihoux and Ragin (2009) suggest best practices on how to deal with these cases. Similar to Villamayor-Tomas et al. (2020) and in line with the suggestion by Rihoux and Ragin (2009), we classify configurations with an inclusion score of 0.75 or higher as sufficient for the outcome, and configurations with an inclusion score of 0.25 or lower as not causing the outcome. This resolves four contradictory rows (9, 11, 15 and 29). The remaining four contradicting configurations (rows 12, 13, 25, and 31) have inclusion scores of 0.5 and 0.6. These can hardly be resolved and are omitted from the minimization process.

Table B.3
Truth table. Logical remainders (9) omitted

#row	Conditions						n	incl	Cases (WUA)
	MEAS	DMAJ	ASIST	TECH	FUENTE	OUT			
1	0	0	0	0	0	1	2	1	2, 4
3	0	0	0	1	0	1	1	1	33
4	0	0	0	1	1	1	1	1	25
7	0	0	1	1	0	1	1	1	58
8	0	0	1	1	1	1	2	1	16, 21
9	0	1	0	0	0	1	6	0.83	3, 5, 7, 48, 50, 57
10	0	1	0	0	1	1	2	1	30, 54
11	0	1	0	1	0	1	4	0.75	10, 18, 43, 60
12	*0*	*1*	*0*	*1*	*1*	*C*	*2*	*0.5*	*9, 42*
13	*0*	*1*	*1*	*0*	*0*	*C*	*5*	*0.6*	*29, 39, 40, 44, 61*
14	0	1	1	0	1	0	1	0	24
15	0	1	1	1	0	1	4	0.75	1, 15, 17, 56
17	1	0	0	0	0	1	1	1	13
18	1	0	0	0	1	0	1	0	22
22	1	0	1	0	1	1	2	1	11, 32
24	1	0	1	1	1	1	1	1	52
25	*1*	*1*	*0*	*0*	*0*	*C*	*4*	*0.5*	*14, 19, 45, 59*
27	1	1	0	1	0	1	1	1	31
28	1	1	0	1	1	1	1	1	12
29	1	1	1	0	0	1	5	0.8	27, 36, 46, 53, 55
30	1	1	1	0	1	1	1	1	26
31	*1*	*1*	*1*	*1*	*0*	*C*	*12*	*0.5*	*6, 8, 20, 23, 28, 34, 35, 37, 38, 41, 47, 49*
32	1	1	1	1	1	0	1	0	51

C(Enhanced) Parsimonious and intermediate solutions for the presence of the outcome.

It is a standard of good practice to present all three types of solutions that can result from QCA. Since the conservative, or complex, solution is reported in the main text, we present here the parsimonious and intermediate solutions. While the parsimonious solution includes all logical remainders as if they caused the presence of the outcome, the intermediate solution does so only according to consistent and intuitive directional expectations (i.e., expectations about whether we expect the presence rather than the absence of each condition to cause the outcome). Both solutions can be further "improved" into enhanced versions (Schneider and Wagemann, 2012). These enhanced parsimonious and intermediate solutions differ from their normal counterparts by excluding contradictory simplifying assumptions, simultaneous subset relations, and incoherent configurations (Dusa, 2019). Tables C.1 and C.2 show the parsimonious and intermediate solutions, and Tables C.3 and C.4 show their enhanced versions.

Table C.1
Parsimonious solution

	Configuration	Inclusion	Coverage	Cases (WUA)
1	~DMAJ*TECH	1	0.140	33, 25, 58, 16, 21, 52
2	~DMAJ*~FUENTE	1	0.116	2, 4, 33, 58, 13
3	~MEAS*TECH*~FUENTE	0.8	0.186	33, 58, 10, 18, 43, 60, 1, 15, 17, 56
4	MEAS*~ASIST*TECH	1	0.047	31, 12
5	MEAS*ASIST*~TECH	0.875	0.163	11, 32, 27, 36, 46, 53, 55, 26
6	~MEAS*~ASIST*~TECH	0.9	0.209	2, 4, 3, 5, 7, 48, 50, 57, 30, 54

Table C.2
Intermediate solution

	Configuration	Inclusion	Coverage	Cases (WUA)
1	~DMAJ*TECH	1	0.140	33, 25, 58, 16, 21, 52
2	~DMAJ*~FUENTE	1	0.116	2, 4, 33, 58, 13
3	~MEAS*TECH*~FUENTE	0.8	0.186	33, 58, 10, 18, 43, 60, 1, 15, 17, 56
4	MEAS*~ASIST*TECH	1	0.047	31, 12
5	MEAS*ASIST*~TECH	0.875	0.163	11, 32, 27, 36, 46, 53, 55, 26
6	~MEAS*DMAJ*~ASIST*~TECH	0.875	0.163	3, 4, 7, 48, 50, 57, 30, 54

Parsimonious and intermediate solutions are equal for configurations 1–5 and differ only in configuration 6. The spotted difference is that the intermediate solution includes DMAJ to the configuration and the parsimonious does not. The WUAs they represent, however, are similar.

Table C.3
Enhanced parsimonious solution

	Configuration	Inclusion	Coverage	Cases (WUA)
1	∼MEAS*∼DMAJ*TECH	1	0.116	33, 25, 58, 16, 21
2	∼MEAS*DMAJ*∼ASIST*∼TECH	0.875	0.163	3, 5, 7, 48, 50, 57, 30, 54
3	∼DMAJ*ASIST*FUENTE	1	0.116	16, 21, 11, 32, 52
4	MEAS*DMAJ*∼ASIST*TECH	1	0.047	31, 12
5	MEAS*DMAJ*ASIST*∼TECH	0.833	0.116	27, 36, 46, 53, 55, 26
6	∼DMAJ*∼ASIST*∼TECH*∼FUENTE	1	0.070	2, 4, 13

Table C.4
Enhanced intermediate solution

	Configuration	Inclusion	Coverage	Cases (WUA)
1	∼MEAS*∼DMAJ*TECH	1	0.116	33, 25, 58, 16, 21
2	∼MEAS*DMAJ*∼ASIST*∼TECH	0.875	0.163	3, 5, 7, 48, 50, 57, 30, 54
3	MEAS*∼DMAJ*ASIST*FUENTE	1	0.070	11, 32, 52
4	MEAS*DMAJ*∼ASIST*TECH	1	0.047	31, 12
5	MEAS*DMAJ*ASIST*∼TECH	0.833	0.116	27, 36, 46, 53, 55, 26
6	∼DMAJ*∼ASIST*∼TECH*∼FUENTE	1	0.070	2, 4, 13

Enhanced parsimonious and enhanced intermediate solution are also equal for configurations 1, 2, 4, 5, and 6 and differ only in configuration 3. The difference here is that the intermediate solution includes MEAS in the configuration and the parsimonious does not. The WUAs they represent, however, are also here quite similar.

With respect to the conservative solution from the main text, we find little difference. The conservative solution closely resembles the enhanced versions of the parsimonious and intermediate solutions. This is not surprising as the number of logical remainders used for minimization is gradually reduced. Comparing the conservative solution with the other two enhanced solutions, we find that configurations 2, 3, 4, 6, and 7 are equal, while only configurations 1 and 5 are slightly different. We interpret this as proof for the robustness of the results.

DSeparate analysis for the 2018 and 2022 datasets

Analysis of necessity

The analysis of necessity is presented simultaneously for both years (Table D.1). For the 2018 dataset, no condition reaches the consistency score of 0.9 in order to be accounted for as necessary (although DMAJ comes close with a consistency score of 0.889 for the absence of the outcome). For the 2022 dataset, however, DMAJ reaches a consistency of 0.895 for the presence of the outcome and full consistency for the absence of the outcome. This means that DMAJ is present in most (or all) cases where the outcome is present (or absent). For the presence of the outcome, the coverage score is relatively high (0.654), making it a relevant necessary condition. The relatively low coverage score (0.346) for the absence, however, indicates that DMAJ is a rather irrelevant necessary condition, because there are comparatively many more cases where DMAJ is present than cases where SATISF is absent.

Table D.1
Analysis of necessity, separated for 2018 and 2022

	Presence of outcome (SATISF)				Absence of outcome (∼SATISF)			
	Consistency (inclN)		Coverage (covN)		Consistency (inclN)		Coverage (covN)	
	2018	2022	2018	2022	2018	2022	2018	2022
MEAS	0.357	0.526	0.625	0.667	0.667	0.556	0.375	0.333
DMAJ	0.643	**0.895**	0.692	0.654	0.889	**1.000**	0.308	0.346
ASIST	0.429	0.632	0.706	0.632	0.556	0.778	0.294	0.368
TECH	0.536	0.474	0.750	0.643	0.556	0.556	0.250	0.357
FUENTE	0.393	0.158	0.786	0.750	0.333	0.111	0.214	0.250
∼MEAS	0.643	0.474	0.857	0.692	0.333	0.444	0.143	0.308
∼DMAJ	0.357	0.105	0.909	**1.000**	0.111	0.000	0.091	0.000
∼ASIST	0.571	0.368	0.800	0.778	0.444	0.222	0.200	0.222
∼TECH	0.464	0.526	0.765	0.714	0.444	0.444	0.235	0.286
∼FUENTE	0.607	0.842	0.696	0.739	0.667	0.889	0.261	0.333

Analysis of sufficiency

Generally, the analyses presented here follow the same specifications (as e.g., cutoff points) as the analysis presented in the main text.

2018

The minimization yields four models that group the sufficient configurations for the outcome. Since they all show the same inclusion score of 1 (stating that 100% of cases with present outcome are covered by the model), we only present the first model. Configurations 1–5 are the same for all models, while configurations 6–8 vary between models.

Table D.2
Conservative solution, 2018 data

	Configuration	Inclusion	Coverage	Cases (WUA)
1	~MEAS*DMAJ*~ASIST*~TECH	1	0.179	3, 5, 7, 28, 33
2	~MEAS*~DMAJ*TECH*FUENTE	1	0.143	24, 26, 16, 21
3	MEAS*ASIST*~TECH*FUENTE	1	0.107	11, 35, 29
4	~DMAJ*~ASIST*~TECH*~FUENTE	1	0.107	2, 4, 13
5	DMAJ*ASIST*~TECH*~FUENTE	1	0.071	32, 30
6	~MEAS*~ASIST*~FUENTE	1	0.321	2, 4, 37, 3, 5, 7, 10, 18, 27
7	MEAS*DMAJ*~ASIST*TECH	1	0.071	34, 12
8	MEAS*DMAJ*ASIST*FUENTE	1	0.071	29, 36

As presented in Table D.2, all configurations have an inclusion score of 1, denoting that no contradictory cases were included in the minimization process. Configurations 1, 2, and 6 together explain 64.3% of cases. Comparing these solutions to those in the main text, we do see some similarities. Configuration 1 from the 2018 analysis corresponds to configuration 2 from the joint analysis in the main text. Furthermore, configuration 3 from the joint analysis is expanded by the FUENTE condition to build configuration 2 in the 2018 analysis. Overall, the condition FUENTE tends to appear more frequently in the 2018 data analysis.

2022

Table D.3 presents the conservative solution that has an overall inclusion score of 0.909 and consists of four sufficient configurations, whereof only the first can be considered somewhat important, as it covers more than 26% of cases where the outcome is present.

Table D.3
Conservative solution, 2022 data

	Configuration	Inclusion	Coverage	Cases (WUA)
1	MEAS*DMAJ*~TECH*~FUENTE	0.833	0.263	12, 26, 3, 13, 20, 22•
2	~MEAS*DMAJ*~ASIST*FUENTE	1	0.105	21, 9
3	~MEAS*ASIST*TECH*~FUENTE	1	0.105	25, 23
4	MEAS*~DMAJ*ASIST*TECH*FUENTE	1	0.053	19

Comparing the solution presented in the main text, we observe that the 2018 data replicates one of its configurations (configuration 1) exactly and one closely (configuration 2). These are also the configurations with the highest coverage scores from the 2018 analysis. For the 2022 data, the most important configuration in terms of coverage (configuration 1) is not replicated in the joint analysis. However, it differs only in condition (~FUENTE in 2022 compared to ASIST in the joint analysis).

E. Analysis of sufficiency for the absence of outcome (~SATISF)

The analysis of sufficiency for the absence of SATISF yields a truth table with a large number of contradictions (Table E.1). Without making strong assumptions about cutoff values, this result yields only three “clean” cases: WUAs 22, 24, and 51.

Table E.1
Truth Table for the outcome being the absence of satisfaction (~SATISF)

MEAS	DMAJ	ASIST	TECH	FUENTE	OUT	n	incl	PRI	cases
0	0	0	0	0	0	2	0	0	2, 4
0	0	0	1	0	0	1	0	0	33
0	0	0	1	1	0	1	0	0	25
0	0	1	1	0	0	1	0	0	58
0	0	1	1	1	0	2	0	0	16, 21
0	1	0	0	0	0	6	0.167	0.167	3, 5, 7, 48, 50, 57
0	1	0	0	1	0	2	0	0	30, 54
0	1	0	1	0	C	4	0.25	0.25	10, 18, 43, 60
0	1	0	1	1	C	2	0.5	0.5	9, 42
0	1	1	0	0	C	5	0.4	0.4	29, 39, 40, 44, 61
0	1	1	0	1	1	1	1	1	24
0	1	1	1	0	C	4	0.25	0.25	1, 15, 17, 56
1	0	0	0	0	0	1	0	0	13
1	0	0	0	1	1	1	1	1	22
1	0	1	0	1	0	2	0	0	11, 32
1	0	1	1	1	0	1	0	0	52
1	1	0	0	0	C	4	0.5	0.5	14, 19, 45, 59
1	1	0	1	0	0	1	0	0	31
1	1	0	1	1	0	1	0	0	12
1	1	1	0	0	0	5	0.2	0.2	27, 36, 46, 53, 55
1	1	1	0	1	0	1	0	0	26
1	1	1	1	0	C	12	0.5	0.5	6, 8, 20, 23, 28, 34, 35, 37, 38, 41, 47, 49
1	1	1	1	1	1	1	1	1	51

Since neither the conservative nor the intermediate solution can simplify the three cases by more than the case configurations themselves, there is no analysis to be done. This shows that, as the WUAs have nothing in common that could be minimized, it is not possible to express the absence of satisfaction in a more parsimonious way.

F. WUA names of solution terms

Table F.1
WUA names of solution terms from the joint analysis (main text). Dots (•) mark contradictory cases

Configuration	Cases (WUA)	WUA names
1	33, 58, 10, 18, 43•,60, 1, 15•, 17, 56	Cuatro Vegas Almeria, CR San pedro apostol de godilleta, sectores X y XI, Juan Martinez Parras, CR del paramo alto•, CR la virgen del aviso, tamarite_la concepcion, zairin•, canal de la margen izquierda del genil, CR de la margen izquierda del rio bembezar
2	3, 5, 7, 48, 50•, 57, 30, 54	villamayor, alzira, “burjasot, godella y rocafort”, Sindicato de riegos de Rabal, CR Urdan (CR Nuez de Ebro)•, CR de Burriana, C.R. Bajo Guadalquivir, Real Acequia Moncada
3	33, 25, 58, 16, 21	Cuatro Vegas Almeria, Canal de la cota 100 Margen derecho del rio Mijos, CR San pedro apostol de godilleta, san onofre torromendo, Comunidad de Regantes de Alhama de Murcia
4	27, 36, 46, 53, 55•, 26	S.C. Embalse Villameca, CR ciudad de santa fe, CR del canal alto de Villares, CR de tres consejo, CR Presa de la Vega de abajo•, C.G. Bardenas
5	11, 32, 52	acequia de tormos, C.R. Tajo Segura Librilla, CR Totana
6	2, 4, 13	junta de acendados de la huerta de murcia, canal de castellon, favara
7	31, 12	C.R. Casinos, palazote la herrera

Note: “Cuatro Vegas Almeria” (WUA 33) and “CR San pedro apostol de godilleta” (58) repeat in solutions 1 and 3.

Data availability

Data will be made available on request.

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