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Robust irrigation system institutions: A global comparison

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Robust irrigation system institutions: A global comparison

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Abstract:	In many places irrigation systems rely on robust governance for continued existence. Elinor Ostrom listed design principles that should achieve robust governance, but doubted that any list could be both necessary and sufficient to result in robust governance. To date this assumption has never been formally tested. We conduct a meta-analysis and ultimately evaluate 62 case studies via fuzzy-set qualitative comparative analysis to identify necessary/sufficient conditions for robust irrigation system governance. We identify four necessary conditions and seven configurations sufficient for robust governance. Further, we identify a union of conditions that, when absent, are likely to result in system failure.
Suggested Reviewers:	Avril Horne avril.horne@unimelb.edu.au He has good irrigator credentials
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Response to Reviewers:	Reviewer #1: The comments have been addressed in an appropriate way. What is missing in the appendix given that the authors say that they provide the data "upon request". If data is not included in the appendix, this should be made available publicly, not "upon request" ----------- Thank you for the reviewer's comment. The data is included and can be accessed in the supplementary material. ---------- Reviewer #2: I think the manuscript has quite improved and I think it is almost ready to be accepted for publication in GEC. Optionally, I do think that coding mechanisms should be further clarified. In fact I do have issues with the 1 coder solution as I think it is prone, even with all the precautions one can take, to biases that are inbuilt in how we perceive and understand written text. One thing that could be done, is to show examples of specific text coded (i.e. period xyzzy was indicative of fully in, almost in, almost out, fully out etc..). This can be done by adding example of text in Table 1 of the supplementary material. I also acknowledge that having more than 1 coder requires resources that are not always

	available, though it should lead to more robust results, and the work presented here is really great. Another option is to assess which cases present in this paper were also coded by Cox et al or Baggio et al. and assess whether there are differences in the coding. This because the ratio of missing value in this work seems quite lower than in Cox or Baggio's work. Finally, there is a typo at the beginning of the supplementary (I think interceding reliability should be intercoder reliability) ------- Thank you for the reviewer's comments. Following your suggestion, we include the sample of coded data for the fuzzy-set in the supplementary material in Table 9 and 10. Unfortunately, we could not compare our coded data with that of Cox et al (2010) and Baggio et al (2016) since both articles only provide data noting the 'presence' or 'absence' of the design principles on aggregate, without referring to each case. Finally, the typo in the supplementary material has been fixed. Thank you for noting that. ------------ Reviewer #3: The editors have addressed all my concerns satisfactorily. This is a very interesting contribution. Congratulations. ------------ Thank you.

June 13, 2019

Prof N. Jennings
Managing Editor
Global Environmental Change

Dear Prof Jennings,

We wish to submit the manuscript entitled *Robust irrigation system institutions: A global comparison* to be considered for publication in Global Environmental Change. The manuscript has not been published elsewhere, nor has it been submitted simultaneously with any other publication.

In this paper, we diagnose 62 irrigation governance systems across 37 countries using Ostrom's Design Principles (DP). The paper addresses Ostrom's questions about necessary and/or sufficient DP conditions for robust common property regime in the case of water. The paper offers some enhancements to Ostrom's DPs in manner that may assist others involved in searching for ways to improve the management of irrigation systems, and the governance of water more generally.

We have no conflicts of interest to disclose. Thank you for your consideration of this manuscript.

Kind regards,

Sitti Rahma Ma'mun

Robust irrigation system institutions: A global comparison

1. Introduction

There are many examples of common property ~~resources~~ regimes (CPRs) such as fishery, forestry, pasture and water ~~supplies~~supply~~)~~ that involve collective self-governance arrangements. Within that list of CPRs, small-scale irrigation water ~~systems~~ institutions often provide effective self-governance exemplars that are long-lasting (e.g. Janssen and Anderies, 2013). Shepsle (1989) defines long-lasting institutions as *robust*, especially where operational rules are devised and modified over an extended period ~~but~~ so that desired system characteristics remain ~~despite component part or environmental changes~~. Robust water governance institutions persist because, under duress, they are able to p~~p~~roduc~~ing~~e efficient, socially-acceptable outcomes (Young, 2014).

An issue for future robust water governance is that many current ~~systems~~ institutions were established during eras when there was abundant supply (Randall, 1981; Turton, 1999; Wheeler et al., 2017; Young, 2014). ~~.~~Increased water demand and rapid environmental change is testing those ~~governance~~ institutional arrangements, leading to concerns about future water crises (World Economic Forum, 2019) and attempts to identify robust water policy and institutional reforms (Gruère and Le Böedec, 2019). In an effort to identify institutional arrangements that would result in best outcomes ~~from~~ for ~~common property resource~~ CPR ~~governance arrangements~~ Ostrom (1990) provided a list of design principles (DPs) based on common findings from detailed case studies of 80 irrigation and fishery ~~systems~~institutions. The DPs included factors that may improve the probability of collective action and robust water ~~governance~~ institution~~s~~al arrangements in the face of scarcity and uncertainty.

Collective action should be most prominent where property rights are shared equally among users ~~as common property resources (~~in CPRs~~)~~, although free-riding and rivalry problems may reduce collective organisation (Feeney et al., 1990; Ostrom, 1990). CPRs are

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different from open access resources to which no right of any kind is assigned (McKean, 1992; Quiggin, 1988), and their study can be traced back to the work of Gordon (1954) on an economic theory of fisheries. Thus, CPRs are not private or public property; they are geographically confined resources (Dasgupta, 2005) that are subject to the rights of common use by a group of co-equal owners (Ciriacy-Wantrup and Bishop, 1975). Ostrom's governance DPs for CPRs have been applied to the study of collective action, and updated in response to criticism that they may be too general in nature (Cleaver, 2000). Notable Original CPR research detailing institutional arrangements for successful governance outcomes include Wade (1989), Ostrom (1990) and Baland and Plateu (1996). These studies find found that neither private nor state control determines the sustainability of common pool resourcesCPRs, but rather success comes fromfrom the -robustness of- self-governing institutions and, in particular, their capacity to that persist in an attempt to sustain the productive use of a resource as conditions and demands changes. Typically, these institutions y are characteriszed by complex rules that allow members of a community to share access to the CPR.

Questions remain, however, as to whether Ostrom's CPR governance arrangement DPs are necessary – or necessary and sufficient – conditions to ensure sustainability and long-lived robustness (Ostrom, 2009). Ostrom herself doubted that any list of DPs would be necessary and sufficient to ensure robustness, and although this would be supported by a general scan of the literature (Mahoney et al., 2009), no test has been carried out to date. Nevertheless, hOstrom'ser principles have been widely widely applied as an analytical framework to help with the evaluatione/diagnoseis of the effectiveness of local common property resource institutionsCPRs including irrigation systems (Cox et al., 2010), and multiple common property resource systems to examine the co-occurrence or combination of DPs leading tonecessary for social and ecological success (Baggio et al., 2016b). Her principles have also been used to assess case studies of success and failure in governance (Barnett et al., 2016), and

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also the scope and scale limits of analytical approaches involving the use of synthesis, meta-analysis and validation methods (Ratajczyk et al., 2016). However, these studies are not typically clear with regard toWhile these studies have therefore established measures of success across multiple CPRs (e.g. fishery, forestry and irrigation using presence/absence conditions), questions remain as to whether Ostrom's CPR institutional DPs are necessary—or necessary and sufficient—conditions to ensure sustainability and long-lived robustness (Ostrom, 2009). Ostrom herself doubted that any list of DPs would be necessary and sufficient to ensure robustness, and this is supported by a general scan of the literature (Mahoney et al., 2009). To explore this question, we focus solely on an evaluation of irrigation institutions via the DPs to determine whether their institutional arrangements appear to be , are robust, fragile or prone to a failure. These outcomes are particularly important what comprises successful governance systems, nor do they typically examine robust institutions which are an important factors for future water governance arrangements, under expectations of scarcity and uncertainty with respect to supply (Young 2014). Water is a unique resource that can be used multiple times, across multiple locations, making robust adaptation to future uncertainty challenging. Many water resources have an additional challenging characteristic. Water tends to flow in a single direction with the consequence that the impacts of (ab)use tend to be uni-directional. In this paper we seek to answer Ostrom's (2009 p.16) questions about necessary and/or sufficient DP conditions for irrigation governance systems. WTherefore, in this paper, we search for the presence/absence or links between necessary conditions and/ explore whether there are groups/combinations/configurations of sufficient conditions that constitute alternative pathways toand robust institutions in the field using a large-N case study approach. Finally, we will Based on our findings, we then offer some possible enhancements to Ostrom's DPs in an attempt to manner that may assist others involved in searching for ways to improve the management of irrigation systemsinstitutions, and the use of water.

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2. Theoretical framework

The overarching basis for our study is the theory of collective action which seeks to understand what factors enable some groups to achieve difficult collective outcomes, while others ~~fail (~~fail (Ostrom, 2011). Consistent with a focus on empirical validation of resource governance institutions (Janssen and Anderies, 2013), we apply Ostrom's DPs as updated by Cox et al. (2010), and used ~~endorsed~~ by Ostrom in the address she gave when ~~when~~ she accepted her Nobel Prize (2010). The updates ~~have~~ resulted in a total of 11 DPs, which span the boundaries of a resource system, local conditions, rules and organi~~s~~zational arrangements, monitoring, conflict resolution and sanctions, and rights recognition within nested enterpr~~ise~~i~~z~~ses~~s~~ (Table 1).

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Table 1. DPs modified by Cox et al. (2010) and endorsed by Ostrom (2010)

	Design Principles
1A.	*User Boundaries*: Clear and locally understood boundaries between legitimate users and nonusers are present.
1B.	*Resource Boundaries*: Clear boundaries that separate a specific common-pool resource from a larger social-ecological system are present.
2A.	*Congruence with Local Conditions*: Appropriation and provision rules are congruent with local social and environmental conditions.
2B.	*Appropriation and Provision:* appropriation rules are congruent with provision rules; the distribution of costs is proportional to the distribution of benefits.
3.	*Collective Choice Arrangements*: Most individuals affected by a resource regime are authorized to participate in making and modifying its' rules.
4A.	*Monitoring Users*: Individuals who are accountable to, or are, the users monitor the appropriation and provision levels of the users.
4B.	*Monitoring the Resource*: Individuals who are accountable to, or, are the users monitor the condition of the resource.
5.	*Graduated Sanctions*: Sanctions for rule violation start very low but become stronger if a user repeatedly violates a rule.
6.	*Conflict Resolution Mechanisms*: Rapid, low cost, local arenas exist for resolving conflicts among users or with officials.
7.	*Minimal Recognition of Rights*: The rights of local users to make their own rules are recogni~~s~~zed by the government
8.	*Nested Enterpri~~sz~~ses*: When a common-pool resource is closely connected to a larger social-ecological system, governance activities are organ~~ise~~ized in multiple nested layers.

The presence/absence of institutional arrangements that are consistent with these DPs may help in informing whether or not CPR ~~management systems~~institutions can be improved, and whether they are prone to failure as discussed by Ostrom (2011) during her reflection on the work of Coman (1911). In th~~is~~at work, Ostrom offered advice on ways that specific institutional arrangements in particular contexts can increase the effectiveness of irrigation systems' management, and ways to assess when collective management may produce outcomes that are superior to private or public property rights. Building on that work, ~~in this paper~~ we focus on case studies of common property ~~resources~~regimes, rather than common pool resources as studied by Ostrom (1990, 2010). In particular, we focus on the institutional arrangements that determine how a resource is used and, when they fail, abused. Finally, we search for the relationship between DPs and robust water ~~governance arrangements~~institutions

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that have not featured in previous research. As a criterion for success, we apply the earlier definition of robust institutions as the system outcome, where irrigation ~~system~~ governance arrangements persist under duress producing efficient use, investment preservation, and socially-acceptable outcomes. Table A2 in the ~~Supplementary Material~~ Appendix to this paper details the definition of successful robust outcomes, while the following section details our analytical method and approach in greater detail. Far greater detail can also be found in the Supplementary Material for this paper.

3. Methods and materials

This study employs a meta-analysis approach based on identifying what does and does not work in the governance of irrigation systems. Other studies have noted limits to the comparison of global assessments in this space (Ratajczyk et al., 2016). However, we argue that much can be learned from comparative research~~—especially when it is empirical~~. We begin by searching for irrigation ~~governance systems~~institutions with similarities that make~~s~~ meta-analysis of their key features possible. The methodology we use is based on systematic coding approaches (Poteete et al., 2010b) that use Ostrom's DPs as explanatory variables. ~~Objectivity~~ Coding objectivity requires an iterative process of refining the way each variable is defined through the use of qualitative comparative analysis techniques (Rudel, 2008).

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3.1. Qualitative Comparative Analysis

Qualitative comparative analysis (QCA) bridges quantitative and qualitative data through a capacity to identify decisive cross-case study patterns. The cross-case pattern assessment process is designed to accommodate diversity among cases~~ studies~~ and account for heterogeneity with regard to different causally relevant conditions (Ragin, 1994). QCA approaches can also identify ~~different~~ alternative combinations of conditions capable of generating the same outcome. That is, QCA is grounded in the assessment of complex

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relationshipss among variables, rather than correlation, as necessity and sufficiency are indicated when certain set relations exist. A key feature of QCA is that it allows researchers to reduce the complexity of empirical information to achieve greater parsimony by looking for similarities and differences among cases through logical minimisszation (Schneider and Wagemann, 2012). The approach we use is consistent with As such, Ostrom and Cox's (2010) recommendation for ed the use of QCA approaches for the development of future DPs to deal with the lower-level aggregation of social-ecological systems (SES), especially where small to medium sample sizes preclude the use of more conventional statistical methods. A main strength of QCA is that it can analysze complex causations from small samples and identify the drivers of outcomes from multiple configurations of causal conditions (Ragin, 2009). The method enables assessment of context-specific causality including causal conditions that might have a positive or negative effects depending on the context in which it is set (Marx et al., 2014). To date, QCA has been used to study irrigation institutions by Lam and Ostrom (2010) and (2015) using crisp and fuzzy datasets, respectively, derived from interview methods. Further, Baggio et al. (2016a) assess the presence and absencect of Ostrom's DPs using a crisp-set QCA across forestry, fishing and irrigation three types of CPRs. However, wWhile valuable,; however, although the results from these studies tend to be too general to enable the development of recommendations for a change in the way a specific water resource is governedare too general to draw meaningful conclusions about water governance institutions.

3.2. Fuzzy-set data calibration

In this study, fuzzy-set QCA (*fs*/QCA) methods (i.e. assessment values ranging between 0 and -1) are adopted over the more common crisp-set methods (assessment values set to either 0 or -1). This is justified on the basis that we seek to explain the *degree* of DP membership in the configuration of causal conditions that that may result in the emergence or maintenance of a constellation set of arrangements which that, when working togetherin concert, help to

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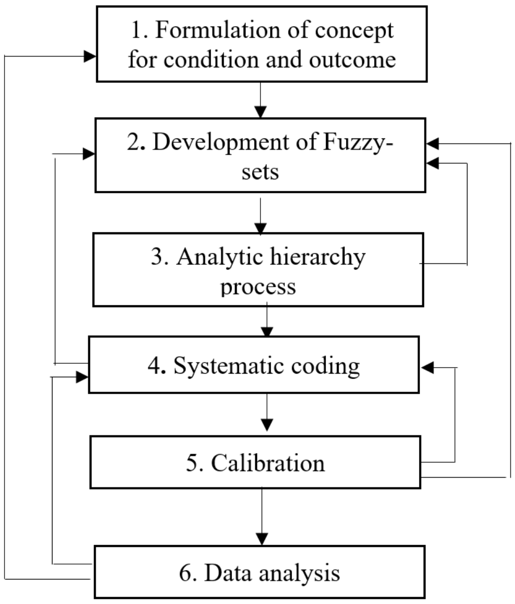
maintain the ~~create a~~ robustness of an ~~structure~~institutions. ~~Robustness i~~In this sense, robustness is determined by institutional ~~the system's~~ capacity to adapt equitably and efficiently to ever-changing supply and demand conditions without variation of the underlying structure and rules that determine the way the institution operates~~its underlying structure~~systems. The underlying structure and rules ~~arrangements within~~associated with each DP condition are not simply present or absent, but vary from context to context and thus require a more graduated metric in a manner that ~~. However, this feature~~ complicates the process significantly.

Development of a well-constructed fuzzy-set requires a well-thought-out calibration process, as the degree of fuzzy set membership strongly influences the result of the analysis (Basurto and Speer, 2012). Consequently, Ragin (2006) recommends attention to transparency and replicability in the membership and calibration processes. Few sources provide explicit procedural advice on how to transform qualitative concepts to fuzzy values (de Block and Vis, 2018). While Basurto and Speer (2012) and Toth, Henneberg and Naude (2017) offer explicit calibration procedures as a part of their research. U~~, u~~nfortunately, t~~. Th~~he calibration process in both studies~~, however,~~ ~~are~~ is not suitable for our data because their calibration was predetermined before the data collection, whereas ours takes place after.~~.~~ Further, we require calibration after the fuzzy set is defined. Thus, we turn to Adcock and Collier's (2001) measurement validity framework and follow the structured calibration procedure set out in Figure 1. We stress that, as indicated by the arrows, this is an iterative process and that care needs to be taken to ensure that the data are well aligned with the theoretical concepts and study objectives.



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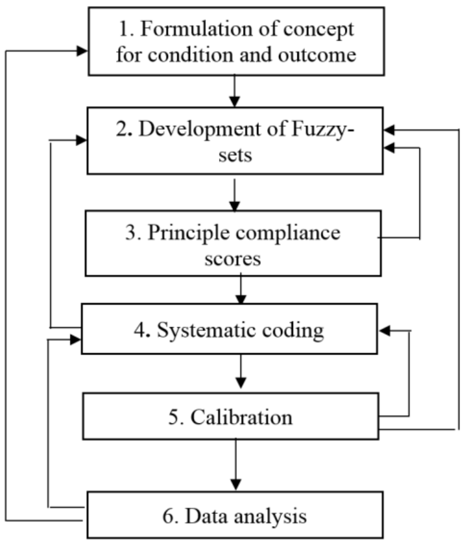

***Figure 1:** Scoring, coding and calibration procedure*

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In *fs*/QCA approaches, the causal conditions selected and outcomes chosen should be based on prior theoretical knowledge and empirical insights gained throughout the research process (Schneider and Wagemann, 2010). Since our study is based on Ostrom's DPs, we use the concept definitions provided by Ostrom (2010) in Table 1 as the basis for our causal conditions. ~~Some~~ However, some of these definitions ~~were~~ are ~~then~~ slightly modified to conform with the irrigation ~~systems~~ institutions under examination as~~(~~ indicated by the **bold** text in Table 1~~)~~.

~~Further, to~~For example, consistent with recommended practice (Schneider and Wagemann 2010), we reduced the total number of conditions by~~, we~~ join~~ed~~ing User Boundary (DP1A) and Physical (resource) Boundary (DP1B) into one condition: ~~*Clearly Defined*~~*Clearly-defined Boundary*. This was done because, in most of the case studies, user boundary is confined within the physical boundary of the irrigation system. That is, ~~the user is usually express~~users are typically socially and physically constrained to the extent of the area covered by the irrigation distribution system. The complete list of final study conditions is provided in Table 2.

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Table 2: *Modifications to Ostrom's DPs for irrigation system case calibration*

Condition (DP)	Definition
1. Clearly-d ~~d~~efined ~~Boundaries~~boundaries	Legitimate users are clearly defined and identifiable. Physical limits on the extent of the resource are defined at all points in time, and across space.
2a. System congruence with local conditions	Appropriation and provision rules are congruent **~~and can be expected to remain congruent~~** with local **and system-wide** social and environmental conditions as they change.
2b. Proportional equivalence between benefit and cost	The benefits obtained by water users are in proportion to fixed and system-wide costs of operation.
3. Collective choice arrangements	Most individuals affected by the operational rules can participate in the processes leading up to rule modification.
4a. Monitoring of users	Monitors are accountable to the users **and have the ~~with~~ enforcement capacity necessary to ~~for~~ ensur~~eing~~ compliance with~~to the~~ appropriation and use rules.**
4b. **Resource system monitoring**	**System-wide monitoring and reporting exists and is reported to users.**
5. Graduated sanctions	Appropriators who violate operational rules face sanctions, preferably graduated.
6. Conflict resolution mechanisms	Appropriators and their officials have rapid access to low-cost local arenas to resolve conflicts.
7. Minimum recognition of rights to organ~~ise~~ize	The rights of local appropriators to devise their own institutional structures and rules are not challenged by external government authorities.
8. Nested enterpr~~ise~~is~~z~~es	Appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities are organized in multiple layers of nested enterpr~~ise~~izes.

3.3. Case selection

The cases for the meta-analysis were sourced from Scopus, Web of Science and Google Scholar using search terms that initially included 'farmers' managed irrigation ~~system'~~institution', 'indigenous irrigation ~~system'~~institution', 'traditional irrigation ~~system'~~institution', and 'water user association'.

To expand the initial list of potential case studies, snow-ball sampling methods were employed. That is, the links and references embodied in the initial articles found were used to source additional material, ~~and~~ which continued to other articles that cited the original ~~one~~ study ~~using~~ via Google Scholar. To reduce any bias that may occur by sourcing only published

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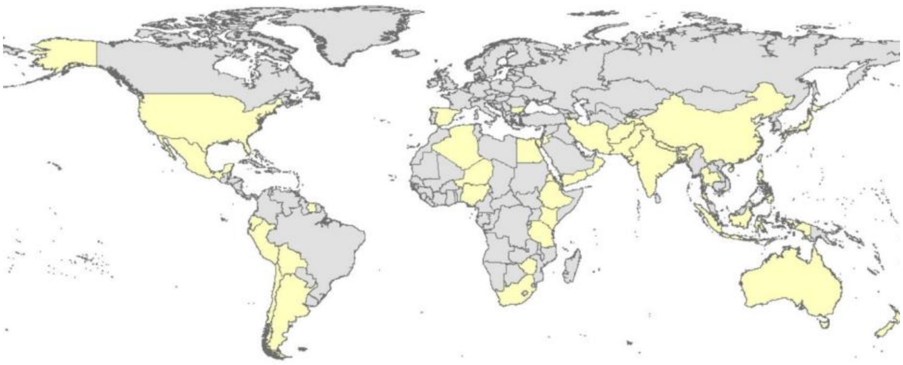
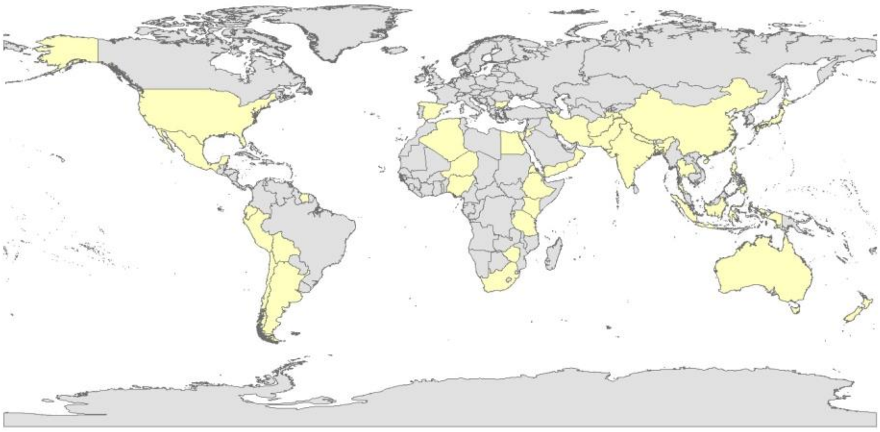
articles, we followed recommendations provided by Poteete, et al. (2010a) and added all articles including those that had not been peer-reviewed in the data~~-~~base. As a result, we ended up with an initial list of 240 potential case studies that were then screened using two inclusion criteria. First~~ly~~, ~~i)~~ the case study article had to examine institutional arrangements in detail. ~~ii)~~Second, where a case study did not provide enough information, we combined two or more articles that discussed the same irrigation ~~system~~ institution ~~as~~ into one case. In addition, we excluded any case studies that used Ostrom's DPs to evaluate planning processes, and (combined or individual) cases studies that did not contain enough information for further analysis. Figure 2 shows the global scope of the case studies with the number per country listed in the caption to this figure (in parentheses). We ended up with 62 case studies located across 37 countries.





Map Source: Esri (2017)

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Figure 2: Case distribution across 37 countries: Afghanistan (1), Algeria (1), Argentina (1), Australia (1), Bangladesh (1), Bolivia (1), Bulgaria (1), China (2), Ecuador (1), Egypt (2), Eritrea (2), Ethiopia (2), Haiti (1), India (2), Indonesia (5), Iran (1), Japan (1), Jordan (1), Kenya (3), Nepal (2), New Zealand (1), Niger (1), Nigeria (1), Oman (1), Pakistan (1), Peru (1), Philippines (2),South Africa (1), Spain (6), Suriname (1), Taiwan (1), Tajikistan (1), Tanzania (3), Thailand (3), United States (4), Yemen, (1), and Zimbabwe (1).

3.4. Development of the fuzzy-set

The preliminary list of sub-sets was derived from best-worst practices typically found in the literature and combined with insights from the case studies (Table A1 of the Appendix). The literature and sub-set of information ~~found~~ was then used to develop systematic coding guidelines. After the first round of the coding, ~~and consistent with the methodology's iterative process, as we proceeded,~~ we refined the fuzzy-sets and coding guidelines in accordance with the methodology's recommended iterative process. As discussed above, a combined condition representing *Clear Boundaries* (BOUND) was ~~undertaken~~ created to ~~reduce overlap~~more accurately represent case realities, and to reduce the total number of conditions for the *fs*/QCA. In the case of water governance ~~systems~~institutions, we ~~defined~~ also specified water use rights as clearly defined if i) users have a right to ~~use~~ abstract a certain amount of water, ii) the location as to where and when water can be abstracted are specified; and iii) the ways that abstracted water can be used are pre-determined (Meinzen-Dick, 2014). Table 3 provides a list of the final fuzzy-set conditions and outcomes. ~~-~~Table A1 of the appendix lists the scoring guideline that were applied~~.~~

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Table 3: Abbreviation of the DPs that are used in the analysis.

Ten Conditions and an outcome	Design Principle	Abbreviation
~~Clearly defined~~Clearly-defined boundaries	DP 1	BOUND
Congruence with local conditions	DP 2A	LOCCON
Proportional COST and benefit	DP 2B	BENFCOST
Collective governance	DP 3	COLLGOV
User monitoring	DP 4A	USERMON
System monitoring	DP 4B	SYSTMON
Graduated sanctions	DP 5	GRADSAN
Conflict resolution mechanisms	DP 6	CONFRES
Minimum right to organ~~ise~~ize	DP 7	RIGHT
Nested enterpr~~ise~~izes	DP 8	NESTENT
Robust institutions	Outcome	ROBUST

3.5. ~~Principle compliance score~~Analytic Hierarchy Process

Transforming the raw case study data into fuzzy-set values always produces some degree of arbitrariness (Skaaning, 2011). To reduce arbitrariness~~ in the process~~, ~~a~~ measurement is needed to translate fuzzy concepts into quantitative scores, that ~~will~~ can be subsequently ~~be~~ transformed into final fuzzy values. For validity, the measurement criteria need to capture meaningful ideas that accurately reflect the concept being used (Adcock and Collier, 2001). ~~To address these issues we~~We ~~therefore,~~ therefore, ~~developed Principle Compliance Scores~~followed the Analytic Hierarchy Process developed by Saaty (1990)~~,~~ ~~involving~~which suggests two-stage pairwise comparisons ~~two steps ahead of~~prior to ~~arriving at~~setting the ~~the~~ final fuzzy scores~~ values.~~. The first pairwise comparison weights the measurement criteria. T~~,~~ ~~and t~~he second pair-wise comparison then compares the fuzzy-set based on all criteria. For example, as described by Saaty (1990), if we were buying a house we could first assess each individual option using a common set of criteria, and then secondly (when all houses were evaluated) use those criteria again to compare the full set of purchase options and identify the best purchase choice.

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~~First~~Thus, we first identified a set of criteria to measure the fuzzy-set using information from the literature and substantive knowledge from the case studies. We then translated the DPs into a series of questions that could be used to identify opportunities to increase the ~~examining what needed to should be improved to achieve robus~~robustness ~~i~~of a ~~t~~ water ~~governance~~ institution~~s~~ (Ostrom, 2009). For example, ~~with~~ for DP1 we identified four major criteria for ~~for of clearly defined~~clearly-defined user/resource boundaries and ~~or (clearly defined~~ water use rights~~)~~ that could be used to increase robustness~~w should lead to robust institutions al arrangements~~. Second, we employed ~~a~~ the two-~~level~~ stage pairwise ranking of ~~the~~ conditions ~~following the Analytic Hierarchy Process; a method for decision making analysis introduced by Saaty (1990). F~~wherein the first stage~~-level pairwise~~ comparison~~s~~ allowed us to

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weight each criterion, and the s~~. S~~econd~~ level~~ stage~~ pairwise comparisons~~ allowed us to determine how much the fuzzy-set complied with each criterion. The resultant pairwise comparison matrixes had a consistency ratio of CR ≤ 0.1, meaning that the priority ranking of the fuzzy-sets ~~were~~ was consistent, and therefore acceptable (Saaty, 2008).

3.6. Systematic coding

Next, a coding system was developed in Nvivo based on the fuzzy sub-sets listed in Table A1 of the Appendix. We conducted content analysis on the 62 cases, and each case was coded according to the fuzzy definitions. A memo was linked to a case whose content did not directly comply with the fuzzy-set, but where the meaning was implied throughout the article. In these cases, the data was coded accordingly. The memo also included citation details from other supporting documents to supplement information from the main case study article. Where possible (and necessary) additional information was obtained via personal communication with case~~-~~study authors to clarify ambiguous data~~issues in the articles~~. All coding was conducted by the first author and, hence,~~, requiring~~ no inter-coder reliability tests were required. In recognition of the fact that this could result in coder bias, however, we developed ~~However, ~~a set of strict procedures to minimize the risk that this could occur as detailed in the Supplementary Materials to this paper~~, were closely followed to ensure minimal bias by the coder~~.~~. Finally, we treated some missing data as 'absent', and coded these using the lowest score in the fuzzy-set.~~

~~We provide some further explanation for this in the results section.~~

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3.7. Calibration of the fuzzy-set scores

Using indirect methods of calibration recommended by Ragin (2006), we transformed the initial fuzzy-set score into one of four values. A full membership value of 1 was assigned to a fuzzy-set with the highest score, indicating the most favo~~u~~rable manifestation of the

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governance institutionalarrangement criteria. A membership value of 0 was assigned to fuzzy-set with the lowest scores, indicating the worst manifestation of the the governance arrangement criteriainstitutional criteriaoutcomes. The A challenge of with fuzzy concepts was is that it is difficult to justify the cross over (threshold) point,; therefore we doid not assign 0.5 values to in the fuzzy-sets. Furthermore, cases with maximum ambiguity (i.e. 0.5 of fuzzy values) cannot be dealt with in *fs*/QCA analysis (Pahl-Wostl and Knieper, 2014). Instead, with due consideration based on i) our theoretical and substantive knowledge of the empirical studies and ii) the distance in a compliance score between full- and non-member, intermediate scores were assigned based on values of 0.33 which indicated whether a governance arrangement was more out than in; and 0.67 for a governance arrangement that was more in than out (Basurto and Speer, 2012). The fuzzy-set values were then assigned to all cases in the fuzzy data matrix.

Missing data and the meaning of zero "0".

3.8.

Out of the 62 cases, there are 46 complete cases, while 16 cases contain missing data. Missing data exist mainly associated with the presence or absence evident in the discussion of of graduated sanction mechanisms (13 cases or 20%) and conflict resolution mechanisms (5 cases or 8%). All missing data were coded initially coded at thewith a lowestzero fuzzy values whichthat resulted in "0" values in the truth table analysis. SHowever, some of the cases with missing data showed a ROBUST outcome. ThereforeTherefore, in a subsequent analysis, we chose to use the lowest fuzzy value since it is more interesting to explore why certain condition isthe absentce (or presumed to be absentce) canof these conditions might not have compromised a lead to the presence of theROBUST outcome s, rather than assuming thate presence of the condition increases robustness leading to the presence of outcome which has been establishedas typically discussed in the literature.

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Therefore, a~~he~~ “0” value in this study has three meanings, i.e. “truly absent” (when the condition was indeed absent), “not in the set” (missing data: when the condition was not specifically discussed ~~mention~~ in the case study~~,~~ and is therefore ambiguous), and “not applicable” (which mainly~~this is especially~~ appl~~y~~ied ~~for~~to nested conditions. ~~, s~~Since most of the case stud~~y~~ies were small scale and there was no indication of ~~it~~them being part of a ~~a~~ complex or larger ~~system~~institution~~s~~, we suspect that in most cases graduated sanctions operate – even though there is no mention of them~~)~~. All of these meanings ~~can~~are ~~be~~ identified and explored in the solution path of sufficiency conditions discussed later.

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~~3.8.~~3.9. *Data analysis*

Finally, we analy~~s~~zed the data using *fs/*QCA v3.0, developed by Ragin and Davey (2017). Based on Ostrom’s views regarding DP lists, the model used for analysis is as follows:

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BOUND*LOCCON*BENFCOST*COLLGOV*USERMON *SYSTMON*GRADSAN*CONFRES*~~RIGHT~~RIGHT*NESTENT	→ ~~ROBUST→~~ ROBUST	(1)

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The above formula simply reflects a hypothes~~ise~~ized combination of DPs that may lead to robust water ~~governance~~ institutions. Capital letters denote that the conditions and outcomes are PRESENT in an irrigation ~~system~~area. However, unlike a regression equation that would consist of dependent and independent variables, the *fs/*QCA model presents its causal conditions in the ~~left~~ left-hand side~~,~~ and the outcome on the right. Further, the process involves Boolean operators as presented in Table 4: logical AND (*) which combines conditions (*set intersect*) to the smallest score, logical OR (+) which joins conditions (*union set*) to the highest score, and logical NOT (~) that signifies the negation of conditions or outcomes (ABSENT) (Ragin, 2009).

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Table 4: Description of Boolean operators used in the study.

Boolean operation	Symbol	Description
Logical AND	*	Combine condition (*set intersect*) to the smallest score
Logical OR	+	Join condition (*union set*) to the highest score
Logical NOT	~	Signify negation (absent) of condition or outcome

Finally, Schneider and Wagemann (2012) recommend that study data are~~is~~ first ~~analysed~~ analyzed for necessary conditions before performing any analysis of sufficiency conditions. By necessary, ~~this~~ we means~~s~~ that whenever outcome Y is present, the condition X ~~i~~was also present. To address this requirement, a truth table was constructed from the fuzzy value matrix prior to sufficiency analysis. It contains rows of all possible combinations of causal conditions. We set the value of 1 for frequency cut-off to identify empirical relevant causal configuration, and 0.80 for consistency cut-off to determine which configuration pass the fuzzy-set theoretic consistency in the Quine-McCluskey minimi~~s~~zation procedure (Ragin, 2009). We then performed a standard analysis of the truth table for configuration of conditions that are sufficient for robust irrigation ~~system~~institutions.

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4. Results

4.1. Necessary conditions

The results of the analysis in Table 5 show the consistency and coverage values are generally high for the presence of DPs in ~~an~~ irrigation ~~system~~institutions, suggesting good approximation of set-relations (Ragin, 2006) and the relevance of DPs for ROBUST outcomes. However, only four of the DPs pass the 0.9 consistency threshold value (Skaaning, 2011) for identification as necessary conditions; that is, BOUND, USERMON, SYSTMON, and RIGHT. Of those, BOUND also has the highest coverage value of 0.98 which indicates the relative importance of this condition compared to others. We also tested necessary conditions for failed

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systems (~ROBUST)~~,~~ and found that only ~BOUND passed the consistency threshold with a value of 0.959 and coverage of 0.870; which is clearly not trivial. This again emphas~~ise~~izes the necessity of clearly defined boundaries for robust irrigation ~~systems~~institutions.

Table 5: Analysis of necessary conditions for robust ~~institutions~~ (ROBUST) and failure (~ROBUST) outcome.~~.~~

~~**Condition**~~	~~**Consistency**~~	~~**Coverage**~~	~~**Condition**~~	~~**Consistency**~~	~~**Coverage**~~
~~BOUND~~	~~**0.949**~~	~~0.985~~	~~~BOUND~~	~~0.087~~	~~0.221~~
~~LOCCON~~	~~0.761~~	~~0.936~~	~~~LOCCON~~	~~0.275~~	~~0.504~~
~~BENCOST~~	~~0.862~~	~~0.880~~	~~~BENCOST~~	~~0.167~~	~~0.441~~
~~COLGOV~~	~~0.833~~	~~0.897~~	~~~COLGOV~~	~~0.210~~	~~0.489~~
~~USERMON~~	~~**1.000**~~	~~0.889~~	~~~USERMON~~	~~0.014~~	~~0.062~~
~~SYSTMON~~	~~**0.971**~~	~~0.950~~	~~~SYSTMON~~	~~0.051~~	~~0.150~~
~~GRADSAN~~	~~0.708~~	~~0.882~~	~~~GRADSAN~~	~~0.307~~	~~0.552~~
~~CONFRES~~	~~0.839~~	~~0.771~~	~~~CONFRES~~	~~0.175~~	~~0.649~~
~~RIGHTORG~~	~~**1.000**~~	~~0.889~~	~~~RIGHTORG~~	~~0.014~~	~~0.062~~
~~NESTEST~~	~~0.738~~	~~0.894~~	~~~NESTEST~~	~~0.284~~	~~0.533~~

ROBUST			**~ROBUST**		
Condition	**Consistency**	**Coverage**	**Condition**	**Consistency**	**Coverage**
BOUND	**0.949**	0.985	~BOUND	**0.960**	0.871
LOCCON	0.761	0.936	~LOCCON	0.855	0.562
BENCOST	0.862	0.880	~BENCOST	0.672	0.635
COLGOV	0.833	0.897	~COLGOV	0.733	0.612
USERMON	**1.000**	0.889	~USERMON	0.653	1.000
SYSTMON	**0.971**	0.950	~SYSTMON	0.858	0.914
GRADSAN	0.708	0.882	~GRADSAN	0.735	0.474
CONFRES	0.839	0.771	~CONFRES	0.305	0.405
RIGHT	**1.000**	0.889	~RIGHT	0.652	1.000
NESTEST	0.738	0.894	~NESTEST	0.756	0.508

Note: **bold** indicates passing the consistency threshold of 0.9 for a necessary condition.

Next, following a process described in Goertz (2006), we create 2 x 2 tables to ~~examine~~ search for~~any~~ sufficiency effects associated with ~~of~~ the four identified necessary conditions ~~identified~~. According to this process, when the bottom right-hand cell (X, ~Y) is equal to zero, a necessary condition is maximally relevant to a sufficient condition. With regard to the DPs for the irrigation ~~systems~~ institutions included in our study, the results ~~reported~~ shown in Table

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6 suggest that, while all of the necessary conditions identified have important sufficiency condition effects, none of them is sufficient on its own ~~alone~~ to produce ~~the~~ a ROBUST outcome. The bottom left-hand cells (~X,~X, ~Y) show~~s~~ reasonable numbers of observations ~~which~~ indicat~~e~~ing that ~~the~~ necessary conditions are not trivial (Goertz 2006). Interestingly, only BOUND has a zero value in the bottom right cell (BOUND, ~ROBUST) which indicates that the ~~*cClearly defined*~~*clearly-defined* *boundary* DP appears to be maximally relevant as a sufficient condition. However, the presence of two cases in the upper left cell (~BOUND, ROBUST) seems to contradict~~s~~ the necessity finding reported above. The two deviant cases were the Nshara and Mkanyeni canals in Tanzania. In these cases, the users were known but water access and risk sharing were inequitable (fuzzy values of 0.33). Both irrigation systems were managed by ethnic groups with significant power asymmetry that lead to inequity in the rights to use water. However, despite th~~e~~is inequality ~~of access to water~~, the self-governing institutions in question had persisted for many generations. This finding agrees with Agrawal's (2001) ~~statement~~ observation that hierarchical social arrangements in the distribution of benefits can be sustainable despite ~~unfair~~ inequitable access sharing, such as those of caste systems or areas with ethnic and/or racial inequality. Rohlfing and Schneider (2013) also suggest deviant cases can be the result of under-specification, i.e. omission of the SUIN condition, which stands for a 'sufficient but unnecessary part of a factor, that is insufficient but necessary for an outcome' (Mahoney et al., 2009). This finding ~~suggests~~ supports our decision to~~that we should~~ examine joined conditions, ~~which~~ and we will return to a consideration of that issue after some discussion of parsimonious solutions below.

Table 6: Necessary conditions for robust irrigation system institutions

Table 5a. BOUND	~BOUND	BOUND
ROBUST	2	41
~ROBUST	19	0

Table 5b. USERMON	~USERMON	USERMON
ROBUST	0	43
~ROBUST	13	6

Table 5c. SYSTMON

	~SYSTMON	SYSTMON
ROBUST	0	43
~ROBUST	17	2

Table 5d. RIGHT

	~RIGHTRIGHT	RIGHTRIGHT
ROBUST	0	43
~ROBUST	10	9

4.2. Analysis of sufficiency conditions

The results of the truth table analysis show there are seven configurations of conditions that are sufficient for ROBUST irrigation system governanceinstitutions, as presented in Figure 3. The notation here follows Fiss (2011) and Ragin and Fiss (2008) who differentiate between core and peripheral or complementary conditions. Core conditions are those that appear in the parsimonious and the intermediate solutions, while peripheral conditions only appear in the intermediate solution (Fiss, 2011). Parsimonious solutions (Table 7) result from including both easy and difficult counterfactual arguments in the logical reminders for the truth table analysis, which in *fs*/QCA terms is the minimum configuration required for the ROBUST outcome to occur Other conditions added in the intermediate solution require simplifying assumptions based on easy counterfactuals alone; thus they are regarded as contributing or complementary conditions (Ragin and Fiss, 2008). The complete set of truth table results are available in Table A3 inof the Appendix to this paper.

Table 7: Parsimonious solutions for ROBUST institutions

Parsimonious solution	Raw Coverage	Unique Coverage	Consistency
USERMON*SYSTMON or	0.971	0.231	0.978
LOCCON*SYSTMON*RIGHT	0.740	0	1.000
Solution coverage: 0.971			
Solution consistency: 0.978			

Figure 3 shows two distinct groups of causal configurations. Group 1 relies on the first parsimonious solution, i.e. the combination of *user monitoring* AND *system-wide monitoring*

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(USERMON*SYSTMON). The USERMON condition is considered present when monitoring of users has a strong enforcement capacity to ensure rule compliance. The SYSTMON condition denotes that a comprehensive monitoring of water resource conditions and status is in place, and results are accessible to all in a timely manner. These characteristics allow the systems and users to adjust as local circumstances vary. Interestingly, in cases where clear GRADSAN or CONFRES conditions—which are considered important in successful CPR management—are uncertain, USERMON AND SYSTMON conditions consistently appear. The paths that treat GRADSAN as 'don't care' reflect data that may be present or absent in the case study but result in the same outcome. Sufficient conditions that include ~GRADSAN (i.e. ~~-~~absence of *graduated sanctions*) are shared by groups of cases that have either i) ~~i)~~ high mutual trust within the community (such as irrigation ~~systems~~ institutions found in Chaisombat, Nishikanbara LID, Shirgin, Tharigat watershed, Ghayl, and Zanjera Danum), ii) ~~or ii)~~ high control over water allocation mechanisms (Falaj Al Khatmeen, Nabargram, Sidi Okba), or iii) both. These cases include evidence of minimum conflict and free~~-~~rider problems, which may suggest reasons as to why the authors did not discuss this DP in detail—and as such may be ~~treated~~ coded as missing data in our analysis. However, in the Nishikanbara in Japan and Ghayl in Yemen cases, the authors discuss the role of social norms and mutual trust that prevent users from free riding. All other cases with ~GRADSAN characteristics display failure (~ROBUST) in the outcome. ~~Similar missing/absent data outcomes in our analysis also applied to the ~CONFRES condition.~~

Conditions	Solution paths for robust institution						
	USERMON*SYSTMON Cov: 0.71; Con: 0.978					LOCCON*SYSTMON*RIGHTORG Cov: 0.74; Con: 1.000	
	1a	1b	1c	1d	1e	2a	2b
BOUND	•	•	•	•	•		
LOCCON	●	●	●	●	●	●	●
BENFCOST	•	•			•	•	⊗
COLLGOV	•	•	•	•		•	•
USERMON	●	●	●	●	●	●	●
SYSTMON	●	●	●	●	●	●	●
GRADSAN			•		•	•	•
CONFRES	•			•	•	⊗	•
RIGHTORG	●	●	●	●	●	●	●
NESTENT		•	•	•	•	⊗	•
Raw coverage	0.520	0.447	0.337	0.433	0.315	0.066	0.080
Unique coverage	0.117	0.029	0.008	0.008	0.022	0.059	0.008
Consistency	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Solution coverage	0.689						
Solution consistency	1.000						

● denotes core condition (present), • denotes complementary or contributing condition (present), ⊗ denotes complementary condition (absent), blank spaces indicate "don't care" situation where a condition could be present or absent. Cov= coverage; Con = consistency.

Conditions	Solution paths for robust institution						
	1a	1b	1c	1d	1e	2a	2b
BOUND	•	•	•	•	•		
LOCCON	•	•	•	•	•	●	●
BENFCOST	•	•			•	•	⊗
COLLGOV	•	•	•	•		•	•
USERMON	●	●	●	●	●	•	•
SYSTMON	●	●	●	●	●	●	●
GRADSAN			•		•	•	•
CONFRES	•			•	•	⊗	•
RIGHT	•	•	•	•	•	●	●
NESTENT		•	•	•	•	⊗	•
Raw coverage	0.520	0.447	0.337	0.433	0.315	0.066	0.080
Unique coverage	0.117	0.029	0.008	0.008	0.022	0.059	0.008
Consistency	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Solution coverage	0.689						
Solution consistency	1.000						

● denotes core condition (present), • denotes complementary or contributing condition (present), ⊗ denotes complementary condition (absent), blank spaces indicate "don't care" situation where a condition could be present or absent.

Figure 3: Sufficient configurations of conditions for robust irrigation institutions (intermediate solution)

Group 2 (2a and 2b) relies on the second parsimonious solution; the combination of *~~c~~Congruence with local condition* AND *~~s~~System ~~wide~~ system-wide monitoring* AND *~~m~~Minimum rights to organ~~ise~~ize* (LOCCON*SYSTMON*RIGHT) as decisive factors ~~in the~~

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~~configuration~~. That is, when users have the authority to self-organ~~ise~~ize and devise operational rules within a defined framework (RIGHT), they can adapt to various conditions as they change (LOCCON) provided they have required information about relevant resources at the right time (SYSTMON). The solution paths for Group 2 treat the BOUND condition as 'don't care', as the presence or absence of that condition ~~both~~ result in the ROBUST outcome. In these cases, the LOCCON condition becomes essential in the configuration. Solution 2a belongs to small communities in Tanzania (Nshara) and Nepal (Raj Kulo and Thulo Kulo) where conflict resolution is missing (~CONFRES). The importance of conflict resolution mechanisms was clearly mentioned in the case stud~~ies~~y introduction material, but then not discussed in the case study findings. However, Raj Kulo and Thulo Kulo both displayed evidence of having installed devices that tracked water distribution more precisely, as a means to reduce conflict (Martin and Yoder, 1988)~~.~~, while in Nshara furrow irrigators adopted equity and fairness principles to prevent conflict (~~Giilingham~~Gillingham 1999).

4.3. Tests of joined conditions

The results above show that all of the conditions which passed the consistency threshold of the necessary condition analysis ~~are~~ were also present in the parsimonious solution paths—except BOUND. However, despite being present in the solution paths for both Groups, which should indicate its' necessity, LOCCON did not pass the original consistency threshold test. This brings us back the issue of SUIN conditions mentioned previously. We hypothes~~ise~~ize that both BOUND and LOCCON are SUIN conditions~~,~~ and that their union (BOUND+LOCCON) may reveal whether they are individually unnecessary or insufficient for ROBUST institutional outcomes, but constitute shared rules necessary for ROBUST irrigation ~~system governance~~institutions. To test this ~~hypothesis~~hypothesis, we use the enhanced XY plot

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(Rohlfing and Schneider, 2013) to determine whether these two conditions can be treated as SUIN conditions. All XY plots were created using *Tosmana* v1.6 (Cronqvist, 2018).

Figure 4a maps the distribution of cases between the BOUND condition and ROBUST outcome to show that, despite being highly relevant with zero cases in Cell 3 (see the centre of figures for cell numbering references), the two deviant cases in Cell 6 contradict the necessity of the BOUND condition as discussed previously. Figure 4b maps the distribution of cases between the LOCCON condition and ROBUST outcomes showing that Cell 1 contains 30 cases which exclude the LOCCON condition from achieving necessity status, notwithstanding it being present in all of the solution paths. This suggests that, consistent with SUIN principles, the presence of LOCCON ensures ROBUST outcomes in cases such as Nshara and Mkanyeni where the BOUND condition is absent. However, the SUIN condition means that cases without BOUND or LOCCON conditions (e.g. Mendoza) will not result in ROBUST outcomes.

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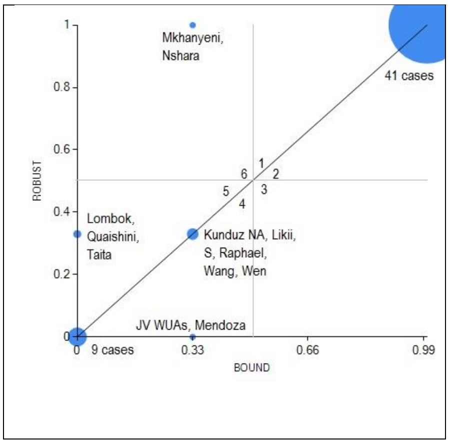

Figure 4a: Enhanced XY plot of BOUND condition

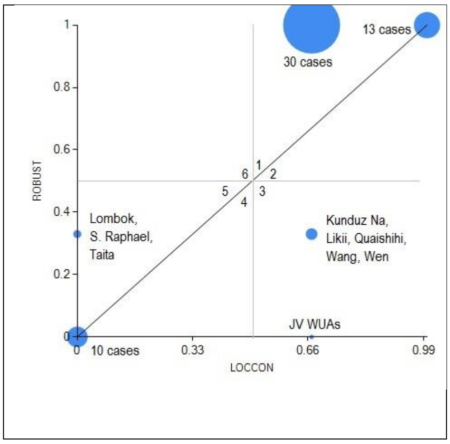

Figure 4b: Enhanced XY plot of LOCCON condition

Unlike the rigid irrigation governance systems in Mendoza, both Mkanyeni and Nshara have flexible working rules for water appropriation including allowing the limited transfer of

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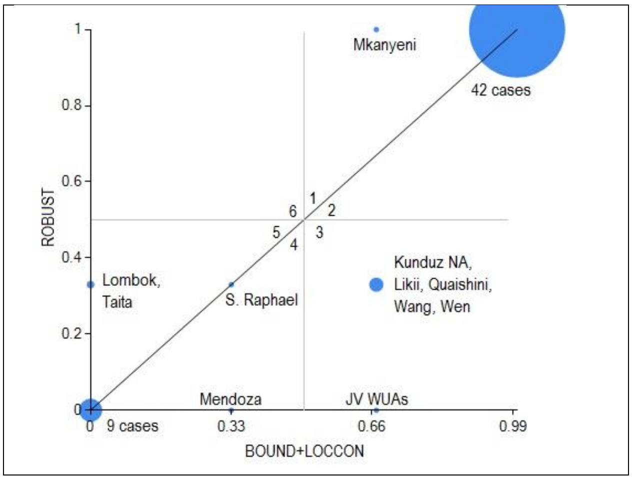
shares and/or allocation.[1] This allows them to reduce some of the inequality dimension between users, supporting the persistence of the institutions for long periods of time. A direct comparison between these cases might not be appropriate, however, since the irrigation system in Mendoza is larger and more complex compared to the small scale irrigation ~~systems~~ institutions of Mkanyeni and Nshara. Nevertheless, we consider that ~~However,~~ comparison ~~here~~ is justified on the basis that the three ~~systems~~ cases were awarded membership in the same fuzzy value category~~,~~; ~~which~~ that is, is more in that out of the BOUND condition, even though they display different outcomes. An additional analysis of the SUIN consistency and coverage values for BOUND+LOCCON reveals a ~~consistency~~ value of 0.978, which suggests that the SUIN condition is necessary. The ~~, and a~~ coverage of 0.936 ~~which also~~ indicates, also, that it is not trivial. Although Figure 5 shows that there are six cases in Cell 3 that reduce the sufficiency effect, it does not contradict the necessary condition evaluation (Goertz, 2006; Rohlfing and Schneider, 2013). This implies that while it is necessary, the SUIN condition alone is not sufficient to achieve ROBUST irrigation system institutions. Figure 5 also shows that there is a deviant case in Cell 1, but the outcome can still be explained by the presence of the condition.

[1] In Nshara, temporary transfer took place within the same irrigation system with neighbours or relatives, providing that whoever borrowed or bought water (although selling water was considered illegal) also participated in maintenance activities. To reduce risk and inequality of water access, farmers in Mkanyeni located their plots in different zones. Shared farming during water shortages also took place for the same purpose.



~~Figure 51~~Figure 5: Enhanced XY plot of BOUND+LOCCON conditions

4.4 Sensitivity analysis

One way to test the robustness of fsQCA analysis is to reduce the number of cases (de Bora et al 2016). We~~ therefore~~, therefore, re-r~~u~~an the analys~~i~~es using complete case studies only, to ~~and found~~discover that GRADSAN and CONFRES are also necessary for ROBUST outcomes. The result is expected ~~since~~because, as discussed earlier, these two conditions ~~are~~were usually the source of missing data. The test for ~ROBUST ~~have~~also returned consistent results showing that only ~BOUND is necessary. Likewise, the truth table analysis ~~shows~~indicates that the parsimonious solutions ~~are~~remained the same, while the intermediate solutions show~~s~~ed only four configurations in Figure 3~~, i.e.~~; that is, 1a, 1c, 1e, and 2b. As a result, we consider that ~~This indicates t~~here is no reason to question the reliability of our ~~results~~findings as a result of the presence of some missing data~~at the results of theour analysis isare generally reliable~~. For further detail, readers are directed to the~~(Please refer to~~ sensitivity analysis section in the ~~s~~Supplementary ~~m~~Materials~~)~~.

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5. Discussion

The results reported above support Ostrom's view that no list of DPs, if complied with, is likely to be ~~would be necessary *and* sufficient for~~ sufficient to ensure institutional robustness ~~governance arrangements~~. ~~But f~~For the irrigation ~~systems~~ institutions included in the study, however, it has been possible to identify a set of four necessary conditions which increase ~~lead to~~ robustness ~~outcomes~~: these are~~at is,~~ ~~clearly defined~~clearly-defined boundaries, user monitoring, system-wide monitoring, and minimum rights to organ~~ise~~ize. The seven configurations of conditions that appear to be sufficient for robustness ~~robust ROBUST outcomes~~ agree with previous studies that have found that not all DPs have~~d~~ to be present in successful CPR management (e.g. Baggio et al., 2016~~b~~). The configuration of causal conditions is context specific. Our findings are c~~, but also c~~onsistent, however, with Ostrom's (2009) view that the presence of more design principles in a self-~~organising~~ organizing institution ~~will~~ increases robustness ~~the probability of robust institutions~~. ~~However, t~~The solution path to 2~~b~~B, however, needs to be treated with cautio~~us~~n as it~~. It~~ includes the absence of proportional benefit and cost as a pathway to ~~the~~ robustness ~~outcomes~~. Three cases in this group, (i.e. Valencia, Bada ~~s~~Spate irrigation and Mkanyeni~~,~~) all have full cost recovery ~~'~~but the distribution of benefits was generally inequitable~~unequal'~~ (fuzzy value 0.33). This ~~perhapspossibly~~ indicates that ~~the calibration for~~ calibrating th~~i~~se concept ~~need to be treated as~~requires treatments of 'more in than out' (0.67), in which the design principle includes the concept of cost recovery that distributed proportionally to the benefit received by the users. In traditional irrigation systems, cost recovery typically is not a major ~~big~~ issue as most ~~since the~~ irrigation infrastructures are ~~were~~ built ~~from simple structures~~ using cheap ~~from surrounding~~ materials sourced from the surrounding landscape, and are thus easier to maintain with labour and in-kind contribution by the farming community. ~~to perform wellFor example, iirrigation institutions delivery may be achieved via ingiessurrounding~~ By contrast, modern irrigation

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delivery systems may be ~~on the other hand, is~~ capital intensive, where the cost of operating and maintaining such systems may not ~~which cannot simply~~ be resolved by in-kind and labour contributions from ~~by~~ farmers. This would indicate ~~Which is~~ why ~~the~~ low-cost recovery has been ~~the~~a concern ~~of the~~for modern irrigation institutions, especially in ~~the~~ developing countries (Sampath, 1992).

The results also found two ~~minimum~~ alternative configurations that consistently ~~appear~~ present in ~~robust~~ institutions characteriz~~s~~ed by robustness. As can be seen ~~, and which are presented~~ in ~~the parsimonious solutions mentioned~~ above,~~. T~~ the causal conditions in the parsimonious solutions mirror the necessary conditions except for that of ~~clearly defined~~clearly-defined boundaries and congruence with local conditions, which we identify as SUIN conditions (discussed below). Given that this study has highlighted the importance of some DPs including clear user and resource boundaries, rules that are congruent with local conditions, monitoring of both users and the resource system, and local rights to organ~~ise~~ize — and the relevance of these DPs as alternative pathways to success — ~~that have appeared~~ we expand upon each of those with some additional examples and detail from the case study materials.

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5.1. ~~Clearly defined~~Clearly-defined boundaries and congruent appropriation rules as SUIN conditions.

In the face of future scarcity and unpredictability, robust water ~~governance~~ institutions must in~~volve CPR~~clude property-right structures that are secure yet ~~flexible~~ adaptable enough to ~~accommodate~~ support change ~~in the systems,~~ while providing incentives for users to invest in maintaining ~~their~~ the resource and~~, also~~ the parts of ~~it~~the system that are under their control ~~system~~ (Howe et al., 1986; Quiggin, 1988). ~~Clearly defined~~Clearly-defined user/resource boundaries and congruent appropriation rules both represent the requisite property rights structure. In our case studies, typical appropriation rules reflect the boundary definition of the

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resource setting: who gets water, when, where, how much and for what use are the shared rules that ~~clearly defined~~clearly and completely define the boundary of the resource system, and at the same time clearly guide~~d~~ the development of working rules that enable efficient and equitable ~~for~~ appropriation. Further, all of the ROBUST outcomes cases displayed some degree of security and flexibility in their institutional arrangements. These two characteristics do not necessarily contradict one other; rather the irrigation community usually managed to design shared access arrangements which allowed users to adapt to changes in supply while respecting the assignment of longer-term ~~the~~ property rights structures (e.g. annual scarcity pressures can be managed separately from longer-term considerations).

Two types of flexibility are typically discussed in the literature, and appear in the cases. First, Ostrom (1990) emphasiz~~s~~es the congruence of appropriation rules with local conditions where water is allocated in response to the changing water availability either by rotation or turn-taking, reducing water proportionally, or assigning different use priorities under different situations. Second, there may be flexibility in the way that longer-term opportunities to access water can be transferred to other uses or users, or from one place to another, as climate, demographic and economic conditions change over time (Howe et al., 1986) ~~and the system must adapt to cope~~. Table ~~7~~8 ~~lists~~ provides some examples of the~~se~~ differences between failed and robust irrigation systems.

Table ~~7~~8: Comparison of failed and robust surface and groundwater irrigation systems

	Failed Systems	**Robust Systems**
Surface water	Kuhl	Tharigat ~~watersed~~watershed
Access to water	Priority of water in kuhls are given to paddy farmers. (Water use right to kharif is formally registered/ documented).	Ten villages shared water in the Tharigat watershed according to a pre-agreed schedule~~ing~~.
Sharing rules at system level	Clear among kuhls irrigation before new entrants started using water in the upper and middle reaches of the irrigation system.	Clear time sharing and rotation schedule for water allocation for each village.
Source of change in the access to water	New entrant: ~~:~~ new rice fields in the upper stream.	New entrant: government takes water from the river in the upper stream to

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		supply drinking water to the nearby city.
Impact or respondse to change in access to water-	Uncontrolled use of water at the upper stream. Useless downstream water rights because irrigation ran dry/system became non-operational.	Water supply decreased significantly. Re-arranged water time sharing and rotation is organised for each village. Proportional rReduction of cultivated area proportionally.
Surface water	Mendoza	Valencia (Old)
Access to water	Proportional to cultivated area. Water right is attached to land.	Proportional to cultivated area. Water right is attached to land.
Sharing rules at system level	Proportional ownership.	Proportional ownership.
Respondse to water shortage/ scarcity	Rotation; Proportional proportional reduction irrespective of different needs.	Applied different priority in short term, long term and emergency planning based on equity principles; proportional reduction.
Impact on access to water	Unable to respond to scarcity or drought. Increased illegal pumping by big farmers to augment water supply.	Different strategy of water allocation allows the system to achieve efficiency while still maintaining equity principles.
Groundwater	Gnangara aquifer system	Eastern La Mancha aquifer system
Access to water	10-year fixed annual entitlement. The licenesing system specified an authoriseized use or purpose to which extracted water is to be put. Water rights are transferable.	Proportional to cultivated area. Water is attached to land.
Respondse to water scarcity	Variability of water resource condition is not considered; information on water condition not readily available.	Reduction of abstraction volume per hectare to increase water level in the aquifer as agreed by farmers' association and water authority.
Impact on water resources	Water overdraft, water resource degradation	Water levels still show downward trend but farmers' association and water authority are building a solid institutional framework in which to introduce sustainable practices.

Whichever sharing/appropriation rule mechanisms apply, there are two main lessons that can be derived from the case studies. First, water water-sharing arrangements at the system level must be in place prior to the need to change allocation arrangements changes occurrsing. Second, while a sense of equity in maintaining user resource sharing in CPR management is important (Quiggin, 1993), in practice the distribution arrangements must be allowed to evolve. Therefore, it is critical to establish individual water use rights that are clearly definedclearly-defined and difficult to contest. Only bythrough gaining secure access to water will users be willing to invest in the operation and maintenance of the system, and to ensure productive use of the irrigation system resources over time. The case studies also assist us to understand how

Formatted: Space Before: 0 pt, After: 0 pt, Line spacing: Double robust ~~governance arrangements~~institutions emerge as a consequence of these conditions. Spate irrigation systems in Eritrea (Ghebremariam and van Steenbergen, 2007; Mehari et al., 2005) have existed for many generations despite unequal access to water. Since this ~~the~~ irrigation ~~systems~~ institutions ~~rely~~ relies on access to seasonal floods, water supply is highly uncertain and unpredictable. As a result, ~~requiring~~ complex arrangements for water appropriation are mixed with other social mechanisms to ensure ~~the community~~ members perceived the rules as fair. This has ~~ensured~~ resulted in continued farmer membership in the resultant ~~collective~~ CPR collective~~management institutions~~. Similarly, in Valencia, the irrigation community maintained equality of access through proportional appropriation rules~~,~~ and applied different access priorities as conditions changed to ensure fair access perceptions by users (Glick, 1970; Maass and Anderson, 1978). Alternatively, Barnett et al. (2016) provide evidence of how the application of proportional access in two groundwater~~-~~-based irrigation systems in Spain became incongruent with the broader economic, social and technological conditions surrounding the system, causing the institutions~~al~~ ~~system~~ to fail. This highlights the relevance of local conditions for robust outcomes, and the importance of ~~flexible~~ property rights structures, as suggested by Quiggin (1988), in~~to~~ keeping the appropriation rules congruent with the nature of the characteristics of the physical resource and social demands on it.

5.2. User and system-wide monitoring

The parsimonious solutions in Table 7 show~~s~~ that the raw coverage of USERMON*SYSTMON is comparatively higher than LOCCON*SYSTMON*RIGHT. In addition, it has a ~~a~~ unique coverage of 0.231 which shows that around 23% of the cases can be explained by this ~~recipe~~solution alone, without the need for others ~~recipe~~. Based on these two features, the USERMON*SYSTMON solution ~~is~~may ~~therefore~~, therefore, be considered more important than the LOCCON*SYSTMON*RIGHT solution. However, i

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~~I~~It is important to note that the concept used for monitoring ~~of~~ users and resources in our systematic coding ~~were~~as slightly different to~~from~~ that of Cox et al. (2010). While separating ~~'~~monitoring of users~~'~~ (DP4A) ~~and~~from the ~~'~~monitoring ~~the~~of resources~~'~~ (DP4B) in their modified~~cation of the design principles~~DPs (see Table 1), Cox et al. (2010) suggest that they indicate ~~explanation indicate~~ the presence of monitoring for both users and resources in DP4A, ~~and~~while DP4B ~~is the~~indicates any accountability of the monitors in the institutions.[2]~~.~~ The same approach was used by Baggio et al (2016). In our view, keeping the two ~~types of~~ monitoring types included in DP4A separate (as in Table 1) is ~~more~~ beneficial in helping to search for and find ways ~~to~~of increas~~ing~~e the ~~in~~~~for analyszing~~ robustness of irrigation institutions~~, since~~as ~~they serve different purposes~~. In our view, c~~C~~ombining the monitoring of individual user behavio~~u~~r~~s and~~ with the benefits of reporting on the status of the entire resources ~~together in DP4A might~~may is about two separate issues ~~undermine the importance of resource monitoring, which may in turn~~that run the risk of being ~~be and~~ ignored~~overlook~~ by researchers when investigating CPRs using ~~Ostroms's~~Ostrom's ~~design principle~~DPs. ~~, as found in some of the case studies.~~

In support of this view, we found evidence of such oversight in some of the case studies. In ~~; for example, T~~the case in Kenya (Likii WRUA) and two cases in China (Wang and Wen villages), for example ~~provide example. In these three cases,~~, the authors clearly identified the presence of monitoring (focusing on users and the status of use), and that the monitors were accountable to users. However, despite the presence of all DPs according to the authors, they observed significant inequality between users (in all cases), ~~the~~ difficulties ~~to~~in copeing with changed ~~in~~ socioecological conditions (Likii WRUA), and over exploitation of water resources

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[2] "*Principle 4A stipulates the presence of monitors, whereas 4B stipulates the condition that these monitors are members of the community or otherwise accountable to those members*." (Cox et al 2010: *Principle 4: Monitoring*). However, the authors reviewed the importance of environmental monitoring for adaptation.

(Wang and Wen villages). These three cases indicate two ~~things~~important points: ~~1~~i) there can be a lack of enforcement despite the presence of accountable monitors and monitoring the users/resources~~;~~, and ii)~~ 2)~~ if resource monitoring does not exist, or the information cannot be accessed in a timely manner to adapt to the social-ecological change, failure is more likely. We coded these three systems as 'fragile'. ~~TBy contrast~~In addition, the comparison~~,~~ of~~ he comparison between two the~~ two groundwater--based irrigation ~~system~~institutions in Table 8 ~~shows~~indicate how monitoring of, and timely available information on, resource conditions clearly contribute to robust institutions. Therefore,

~~E~~establishing an effective individual use monitoring system is important so that aspiring, but ineligible~~ users~~, users can be excluded and that ~~, also, so that~~ allocations, once made, are complied with.

Different from other types of CPR where failure of the system tends to ~~may give~~ impact all ~~to the~~ resource users in the same way, often weak water institutions involve adverse ~~has~~ unidirectional impacts -where the actions of ~~different communities in the~~ upstream users can impose unfair and socially inefficient impacts on ~~and~~ downstream users~~share unequal risk of floods and~~ – especially during short-term water scarcity. This is particularly ~~was~~ evident in~~from~~ the three 'fragile' cases mentioned above. Separate system-wide monitoring should ensure equitable sharing of the available resource~~ and,~~. A~~a~~t the broader level under effective enforcement rules, ~~that~~ eligible downstream users are able to ~~also have to be in place so that access to the total resource that is available for use can be shared. At the system level, the governance and allocation system chosen should have the capacity to enforce sharing rules, ensure that eligible users~~ exercise their rights while not violating others; thus preventing ~~, and prevent any type of~~ infringement upon the common property resource. Further,~~ Thus, an effective user monitoring not only need accountability but also enforcement capacity of the monitors to maintain order and prevent opportunistic behaviour of the competing users.~~

~~In addition,~~ resource monitoring is essential for effective planning and decision-making in natural resource management contexts (Babu and Reidhead, 2000). ~~The fl~~Finally, the flexib~~i~~le~~ity of~~ appropriation and provision rules discussed above ~~critically~~ depend on timely information from the monitoring process, which will inform the need for ~~. Comprehensive monitoring will ensure the ability of~~ the system and users to adapt to various conditions as they change. ~~Importantly~~In support of this conclusion, all of the FAIL cases in this study ~~did not have~~had no proper monitoring systems in place, nor was use infringement or system condition information easily accessible in a timely manner.

~~*5.2.*~~

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~~As we have shown, the persistent of irrigation system institutions is partly determined by the presence of monitoring systems – both of users and of the system itself (e.g. resource and infrastructure conditions). Establishing an effective individual use monitoring system is important so that aspiring, but ineligible users, can be excluded and, also, so that allocations, once made are complied with. Separate system-wide monitoring systems also have to be in place so that access to the total resource that is available for use can be shared. At the system level, the governance and allocation system chosen should have the capacity to enforce sharing rules, ensure that eligible users exercise their rights while not violating others, and prevent any type of infringement upon the common property resource. In addition, resource monitoring is essential for effective planning and decision making in natural resource management contexts (Babu and Reidhead, 2000). The flexibility of appropriation and provision rules discussed above critically depend on timely information from the monitoring process. Comprehensive monitoring will ensure the ability of the system and users to adapt to various conditions as they change. Importantly, all of the FAIL cases in this study did not have proper monitoring systems in place, nor was use infringement or system condition information easily accessible in timely manner.~~

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5.3. Combining congruence principles, ~~system wide~~ system-wide monitoring and the right to organ~~ise~~ize to aspire adaptive capacity~~Minimum recognition of rights to organise~~

~~W~~As outlined above, water is unique compared to other types of natural resources ~~, with~~ . ~~Water has multiple values and uses. I~~as it tends to~~t~~ flow~~s~~ from upstream to downstream, with ~~can thus can have~~ sequential use and re-use values~~,~~ and extremes in terms of quantity, quality and time of impact~~i; its supply also varies in supply in terms of time, place and quality~~ (Hanemann, 2006). It has destructive power during floods~~,~~ or can create severe competition in a long drought. These features make water management ~~is~~ more challenging, especially where management ~~and~~ require~~d~~s rapid adaptation.

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The second parsimonious solution which combine~~s~~d congruence of appropriation and provision rules with local conditions, system monitoring and the minimum right to organ~~ise~~ize (LOCCON*SYSTMON*RIGHT) ~~inspires~~represents a pathway to increased adaptive capacity, and through this system robustness.~~-~~ Consistent with acting upon the information provided from an effective monitoring system, institutional success~~ful CPR management~~ necessitates active group management with the authority to hold members in check over their use of system resources (Bromley, 1992). Most importantly, these arrangements must also be capable of responding to dynamic changes in economic, social and environmental conditions at particular times and places as rapidly as these changes occur ~~with rapid adaptation~~. To achieve rapid adaptation, authority appears to be best left with the local users/managers since they are more familiar to the local context and directly face the immediate changes or problems (Cundill and Fabricius, 2009) but these authorities need to be nested within robust system-wide structures.

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In all irrigation systems, the ~~the~~ minimum information required ~~on time is~~typically includes access to continuously updated information on the quantity of water available ~~ility~~ for ~~the~~ irrigation so that the community and individuals can~~to~~ plan for water allocation and use, and, also, maintain ~~the condition of irrigation~~ infrastructure in a ~~for~~ timely manner~~intenance~~

purposeahead of that allocation and use. The more complex the irrigation delivery system and generally the larger it is, the more important the system-wide monitoring istofor adapting to changed socioecological conditions as they change. Table 8 shows how robust systeminstitutions make used of the information to respond and adapt to various changes ofin water condition including how they; that is,, i.e. adjusting the working rules to keep itmaintain congruence with the local conditions over time (as discussed earlier). InBy comparison, in institutions in the system where information paucity is not readily available to preventes timelyd adaptation and response to socio-ecological change, or where links to larger irrigation systems outside of operating boundaries prevented local modification of operational rules or the system has lack authority to modified their operational rules since it is connected to the larger system which is beyond their boundary (in case of e.g. the Kuhl case study), lead to the declining of the systeminstitutional decline or failure is was the typical outcome. Our analysis finding thatof RIGHT design principles asconstitute a necessary condition for robust outcomes is highly consistent with these arrangementsoutcomes. Local decision-making, however, is only part of the issuesolution;. T there is a need to also incorporate wider political, economic and environmental information into the local decision-making process and prevent resource users in one part of the system having impacts on other parts of the system in a manner that is inconsistent with agreed system-wide rules. ThusThat isus, the right to organiseize locally should not compromise the shared rules at the system level.

5.4. Proposed design principle modifications

Our analysis of 62 irrigation systems corroborates Cox et al.'s (2010) deduction conclusion that Ostrom's DPs are well supported by empirical evidence. The In this study, the *fs*/QCA approach proved to be useful for examining institutional arrangements with respect to each of the design principles in more detail; . However, it also allowed us to identify certain necessary conditions and the minimumalternative configurations of causal conditions that

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~~would~~ could lead to ~~a~~ robust irrigation institutions. Based on this analysis, we are in a position to ~~recommend~~ suggest some further irrigation-system focused ~~enhancements~~ modifications to Ostrom's DPs (Table ~~8~~9) with respect to ongoing congruence (DP 2A), the linking of monitoring to enforcement arrangements (DP 4A), and the clearer reporting responsibility by system monitors to system users—rather than monitoring alone ~~(Table 8)~~ that could be applied to ~~all~~ other irrigation CPRs as a test of their usefulness more generally.~~.~~

Table ~~8~~9: Proposed further modifications to Ostrom's DPs for broad application

	Three DPs as listed in Ostrom (2010)	Modified DPs based on the comparative analysis
2A.	Congruence with Local Conditions: Appropriation and provision rules are congruent with local social and environmental conditions.	Congruence with Local Conditions: Appropriation and provision rules are congruent ~~**and is expected to remain congruent**~~ with ~~**current, and flexible enough to cope with future**~~ local **and system-wide** social and environmental conditions as they change.
4A.	Monitoring Users: Individuals who are accountable to or are the users monitor the appropriation and provision levels of the users.	Monitoring Users: Monitors are accountable to the users **with enforcement capacity necessary to for ensuring compliance with ~~the~~ agreed appropriation and use rules**
4B.	Monitoring the Resource: Individuals who are accountable to or are the users monitor the condition of the resource.	**System-wide monitoring: System-wide monitoring and reporting exists and is reported to users in a timely manner.**

Consistent with Ostrom's desire to test theory with empirical data in this space, we ~~have therefore~~, therefore, offer~~ed~~ these modifications for application and testing by scholars whose work aims to increase the ~~assessment by in future irrigation CPR studies in for the assessment of~~ robustness of irrigation ~~CPR governance systems~~institutions. We would be interested to see tests of necessity and sufficiency in other CPR settings to determine any common DP conditions or the identification of additional alternative solution pathways ~~that emerge~~. Such research would bring us closer to the objectives set out by Ostrom for determining if the DPs continue to stand the test of time—as we hope future water governance ~~systems~~ institutions will.

6. Concluding Comments

The design of water governance and allocation systems remains an art and, while many get to write about opportunities to improve them, very few people are invited to participate in their

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renewal; especially when the necessary changes involve the significant re-specification of the processes and institutional arrangements that determine who gets access to water. Moreover, in the real world of water governance and allocation, there is an immense amount of detail that never gets written down. Our aim, however, was to search for insights that can be used to convince communities that the current suite of ~~arrangements~~ institutions used to manage their water resources are flawed, can be fixed and, if fixed, will help to deliver prosperity. The collection of ~~Evidence~~ evidence from ~~62~~ many case studies across a substantial number of ~~37~~ countries is one way of doing this. The results, which emerged from a careful examination of a fuzzy set of data, identified a) four necessary conditions; b) seven solution path configurations; and, perhaps more importantly, c) a union of conditions that, when absent, are likely to result in system failure during times of stress and/or when demands for access are shifting.

The approach taken attempts to deal, as objectively as possible, with the need for concrete advice in a world where, at best, the concepts are fuzzy and situation specific. We have aimed, as objectively as possible, to come up with a suite of recommendations that c~~w~~ould assist in the transformation of ~~a~~ failing systems into ones that could confidently be described as robust, and also for changes that can be made in order to ensure that systems ~~that~~which are currently performing well continue to do so. That is, we aspire to the development of institutional arrangements that those reliant upon the system's water resources can ~~ould~~ be confident will ~~that it would~~ serve them well, especially in times of stress and as new demands emerge. The recommended ~~enhancements~~ modifications of three of Ostrom's DPs add~~s~~ a new temporal dimension to her work; ~~added~~ emphasis ~~to~~ on the importance of attending to ~~flexible~~ appropriation arrangements designed to facilitate ~~in the face of uncertain~~ change and, also, stressing the importance of monitoring both system-wide and individual use conditions. Our suggested ~~enhancements~~ modifications also identify a need to understand how design

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principles interact with one another. Robustness is enhanced by arrangements that, for example, understand the interdependence of monitoring at differencet scales, allocation arrangements and enforcement capacity.

Finally, the research reported here is reliant on the development of analytical techniques that seek to reduce arbitrariness. All the judgements made are summariseized in the aAppendicesx and Supplementary Material attached to this paper. When it comes to methodology, the highly skewed nature of the data collected suggests a need for more fine-grained analysis. At the moment, the best that we can do is identify relationships among between broad, very fuzzy, concepts. Much more research is needed, for example, on concepts like “enforcement capacity;” “appropriation and use rule” options; and ways to ensure that “appropriation and provision rules are congruent with current, and are expected to remain congruent flexible enough to cope with future, local social and environmental conditions.”

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GEC_2019_671 Reviewer responses

The editors of *Global Environmental Change* have received comments from three of the original reviewers on the revised version and examined your responses to the original reviews. The reviewers are positive about this paper and we are keen to publish it. Before we do so we would like you to take into consideration the suggested edits for clarity made by two of the reviewers.

Reviewer #1:

The comments have been addressed in an appropriate way.

What is missing in the appendix given that the authors say that they provide the data "upon request". If data is not included in the appendix, this should be made available publicly, not "upon request"

Thank you for the reviewer's comment. The data is included and can be accessed in the supplementary material.

Reviewer #2:

I think the manuscript has quite improved and I think it is almost ready to be accepted for publication in GEC.

Optionally, I do think that coding mechanisms should be further clarified. In fact I do have issues with the 1 coder solution as I think it is prone, even with all the precautions one can take, to biases that are inbuilt in how we perceive and understand written text. One thing that could be done, is to show examples of specific text coded (i.e. period xyzzy was indicative of fully in, almost in, almost out, fully out etc..). This can be done by adding example of text in Table 1 of the supplementary material. I also acknowledge that having more than 1 coder requires resources that are not always available, though it should lead to more robust results, and the work presented here is really great.

Another option is to assess which cases present in this paper were also coded by Cox et al or Baggio et al. and assess whether there are differences in the coding. This because the ratio of missing value in this work seems quite lower than in Cox or Baggio's work.

Finally, there is a typo at the beginning of the supplementary (I think interceding reliability should be intercoder reliability)

Thank you for the reviewer's comments. Following your suggestion, we include the sample of coded data for the fuzzy-set in the supplementary material in Table 9 and 10. Unfortunately, we could not compare our coded data with that of Cox et al (2010) and Baggio et al (2016) since both articles only provide data noting the 'presence' or 'absence' of the design principles on aggregate, without referring to each case.

Finally, the typo in the supplementary material has been fixed. Thank you for noting that.

Reviewer #3:

The editors have addressed all my concerns satisfactorily. This is a very interesting contribution. Congratulations.

Thank you.

Highlights

- Ostrom doubts that any list of design principles would be necessary or sufficient for robust outcomes
- We examine 62 irrigation systems in 37 countries and investigate robust outcomes with respect to Ostrom's Design Principles
- The four most important criteria for robust irrigation system are:
  1. Presence of clearly defined boundaries;
  2. User involvement in monitoring and enforcement;
  3. Comprehensive resource condition monitoring,
  4. Minimum rights for users to organize.

Title page

Robust irrigation system institutions: A global comparison

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Abstract

In many places irrigation systems rely on robust governance for continued existence. Elinor Ostrom listed design principles that should achieve robust governance, but doubted that any list could be both necessary and sufficient to result in robust governance. To date this assumption has never been formally tested. We conduct a meta-analysis and ultimately evaluate 62 case studies via fuzzy-set qualitative comparative analysis to identify necessary/sufficient conditions for robust irrigation system governance. We identify four necessary conditions and seven configurations sufficient for robust governance. Further, we identify a union of conditions that, when absent, are likely to result in system failure.

Keywords: common property, qualitative comparative analysis, governance design principles

Acknowledgement

The research described in this paper is part of the study funded by Australian Department of Foreign Affairs and Trade (DFAT) through Australia Awards Scholarship (AAS). We would like to thank our three anonymous reviewers for their insightful comments and important contribution to improve the quality of our paper. We wish to thank Professor Charles Ragin for his generous feedback with respect to our QCA methodology. We would also like to thank relevant authors who helped us clarify any questions that we had about some of the case studies.

Robust irrigation system institutions: A global comparison

1. Introduction

There are many examples of common property regimes (CPRs) such as fishery, forestry, pasture and water supply that involve collective self-governance arrangements. Within that list of CPRs, small-scale irrigation water institutions often provide effective self-governance exemplars that are long-lasting (e.g. Janssen and Anderies, 2013). Shepsle (1989) defines long-lasting institutions as *robust*, especially where operational rules are devised and modified over an extended period so that desired system characteristics remain. Robust water governance institutions persist because, under duress, they are able to produce efficient, socially-acceptable outcomes (Young, 2014).

An issue for future robust water governance is that many current institutions were established during eras when there was abundant supply (Randall, 1981; Turton, 1999; Wheeler et al., 2017; Young, 2014). Increased water demand and rapid environmental change is testing those institutional arrangements, leading to concerns about future water crises (World Economic Forum, 2019) and attempts to identify robust water policy and institutional reforms (Gruère and Le Böedec, 2019). In an effort to identify institutional arrangements that would result in best outcomes for CPR Ostrom (1990) provided a list of design principles (DPs) based on common findings from detailed case studies of 80 irrigation and fishery institutions. The DPs included factors that may improve the probability of collective action and robust water institutional arrangements in the face of scarcity and uncertainty.

Collective action should be most prominent where property rights are shared equally among users in CPRs, although free-riding and rivalry problems may reduce collective organisation (Feeney et al., 1990; Ostrom, 1990). CPRs are different from open access resources to which no right of any kind is assigned (McKean, 1992; Quiggin, 1988), and their study can be traced back to the work of Gordon (1954) on an economic theory of fisheries.

Thus, CPRs are not private or public property; they are geographically confined resources (Dasgupta, 2005) that are subject to the rights of common use by a group of co-equal owners (Ciriacy-Wantrup and Bishop, 1975). Ostrom's governance DPs for CPRs have been applied to the study of collective action and updated in response to criticism that they may be too general in nature (Cleaver, 2000). Original CPR research detailing institutional arrangements for successful governance outcomes include Wade (1989), Ostrom (1990) and Baland and Plateu (1996). These studies found that neither private nor state control determines the sustainability of CPRs, but rather success comes from the robustness of self-governing institutions and, in particular, their capacity to sustain productive use of a resource as conditions and demands change. Typically, these institutions are characterized by complex rules that allow members of a community to share access to the CPR.

Ostrom's principles have been widely applied to evaluate/diagnose the effectiveness of local CPRs (Cox et al., 2010), and to examine the co-occurrence or combination of DPs necessary for social and ecological success (Baggio et al., 2016). Her principles have also been used to assess case studies of success and failure in governance (Barnett et al., 2016), and the scope and scale limits of analytical approaches involving the use of synthesis, meta-analysis and validation methods (Ratajczyk et al., 2016). While these studies have therefore established measures of success across multiple CPRs (e.g. fishery, forestry and irrigation using presence/absence conditions), questions remain as to whether Ostrom's CPR institutional DPs are necessary—or necessary and sufficient—conditions to ensure sustainability and long-lived robustness (Ostrom, 2009). Ostrom herself doubted that any list of DPs would be necessary and sufficient to ensure robustness, and this is supported by a general scan of the literature (Mahoney et al., 2009). To explore this question, we focus solely on an evaluation of irrigation institutions via the DPs to determine whether their institutional arrangements appear to be robust, fragile or prone to failure. These outcomes are particularly important factors for future water governance arrangements under expectations of scarcity and uncertainty with respect to supply (Young 2014). Water is a unique resource that can be used multiple times, across multiple locations, making robust adaptation to future uncertainty challenging. Many water resources have an additional challenging characteristic. Water tends to flow in a single direction with the consequence that the impacts of (ab)use tend to be uni-directional. Therefore, in this paper, we search for necessary conditions and explore whether there are groups/combinations/configurations of sufficient conditions that constitute alternative pathways to robust institutions in the field using a large-N case study approach. Based on our findings, we then offer some possible enhancements to Ostrom's DPs in an attempt to assist others involved in searching for ways to improve the management of irrigation institutions, and the use of water.

2. Theoretical framework

The overarching basis for our study is the theory of collective action which seeks to understand what factors enable some groups to achieve difficult collective outcomes, while others fail (Ostrom, 2011). Consistent with a focus on empirical validation of resource governance institutions (Janssen and Anderies, 2013), we apply Ostrom's DPs as updated by Cox et al. (2010), and used by Ostrom in the address she gave when she accepted her Nobel Prize (2010). The update resulted in a total of 11 DPs, which span the boundaries of a resource system, local conditions, rules and organizational arrangements, monitoring, conflict resolution and sanctions, and rights recognition within nested enterprises (Table 1).

Table 1. DPs modified by Cox et al. (2010) and endorsed by Ostrom (2010)

	Design Principles
1A.	*User Boundaries*: Clear and locally understood boundaries between legitimate users and nonusers are present.
1B.	*Resource Boundaries*: Clear boundaries that separate a specific common-pool resource from a larger social-ecological system are present.
2A.	*Congruence with Local Conditions*: Appropriation and provision rules are congruent with local social and environmental conditions.
2B.	*Appropriation and Provision:* appropriation rules are congruent with provision rules; the distribution of costs is proportional to the distribution of benefits.
3.	*Collective Choice Arrangements*: Most individuals affected by a resource regime are authorized to participate in making and modifying its' rules.
4A.	*Monitoring Users*: Individuals who are accountable to, or are, the users monitor the appropriation and provision levels of the users.
4B.	*Monitoring the Resource*: Individuals who are accountable to, or, are the users monitor the condition of the resource.
5.	*Graduated Sanctions*: Sanctions for rule violation start very low but become stronger if a user repeatedly violates a rule.
6.	*Conflict Resolution Mechanisms*: Rapid, low cost, local arenas exist for resolving conflicts among users or with officials.
7.	*Minimal Recognition of Rights*: The rights of local users to make their own rules are recognized by the government
8.	*Nested Enterprises*: When a common-pool resource is closely connected to a larger social-ecological system, governance activities are organized in multiple nested layers.

The presence/absence of institutional arrangements that are consistent with these DPs may help in informing whether or not CPR institutions can be improved, and whether they are prone to failure as discussed by Ostrom (2011) during her reflection on the work of Coman (1911). In that work, Ostrom offered advice on ways that specific institutional arrangements in particular contexts can increase the effectiveness of irrigation systems' management, and ways to assess when collective management may produce outcomes that are superior to private or public property rights. Building on that work, we focus on case studies of common property regimes, rather than common pool resources as studied by Ostrom (1990, 2010). In particular, we focus on the institutional arrangements that determine how a resource is used and, when they fail, abused. Finally, we search for the relationship between DPs and robust water institutions that have not featured in previous research. As a criterion for success, we apply the earlier definition of robust institutions as the system outcome, where irrigation governance arrangements persist under duress producing efficient use, investment preservation, and socially-acceptable outcomes. Table A2 in the Appendix to this paper details the definition of successful robust outcomes, while the following section details our analytical method and approach in greater detail. Far greater detail can also be found in the Supplementary Material for this paper.

3. Methods and materials

This study employs a meta-analysis approach based on identifying what does and does not work in the governance of irrigation systems. Other studies have noted limits to the comparison of global assessments in this space (Ratajczyk et al., 2016). However, we argue that much can be learned from comparative research. We begin by searching for irrigation institutions with similarities that make meta-analysis of their key features possible. The methodology we use is based on systematic coding approaches (Poteete et al., 2010b) that use Ostrom's DPs as explanatory variables. Coding objectivity requires an iterative process of refining the way each variable is defined through the use of qualitative comparative analysis techniques (Rudel, 2008).

3.1. Qualitative Comparative Analysis

Qualitative comparative analysis (QCA) bridges quantitative and qualitative data through a capacity to identify decisive cross-case study patterns. The cross-case pattern assessment process is designed to accommodate diversity among cases and account for heterogeneity with regard to different causally relevant conditions (Ragin, 1994). QCA approaches can also identify alternative combinations of conditions capable of generating the same outcome. That is, QCA is grounded in the assessment of complex relationships among variables, rather than correlation, as necessity and sufficiency are indicated when certain set relations exist. A key feature of QCA is that it allows researchers to reduce the complexity of empirical information to achieve greater parsimony by looking for similarities and differences among cases through logical minimization (Schneider and Wagemann, 2012). The approach we use is consistent with Ostrom and Cox's (2010) recommendation for the use of QCA approaches for the development of future DPs to deal with the lower-level aggregation of social-ecological systems (SES), especially where small to medium sample sizes preclude the use of more conventional statistical methods. A main strength of QCA is that it can analyze complex causations from small samples and identify the drivers of outcomes from multiple configurations of causal conditions (Ragin, 2009). The method enables assessment of context-specific causality including conditions that might have a positive or negative effect depending on the context in which it is set (Marx et al., 2014). To date, QCA has been used to study irrigation institutions by Lam and Ostrom (2010) and (2015) using crisp and fuzzy datasets, respectively, derived from interview methods. Further, Baggio et al. (2016) assess the presence and absence of Ostrom's DPs using a crisp-set QCA across forestry, fishing and irrigation CPRs. While valuable, however, the results from these studies tend to be too general to enable the development of recommendations for a change in the way a specific water resource is governed.

3.2. Fuzzy-set data calibration

In this study, fuzzy-set QCA (*fs/*QCA) methods (i.e. assessment values ranging between 0 and 1) are adopted over the more common crisp-set methods (assessment values set to either 0 or 1). This is justified on the basis that we seek to explain the *degree* of DP membership in the configuration of causal conditions that result in the emergence or maintenance of a set of arrangements that, in concert, help to maintain the robustness of an institution. In this sense, robustness is determined by institutional capacity to adapt equitably and efficiently to ever-changing supply and demand conditions without variation of the underlying structure and rules that determine the way the institution operates. The underlying structure and rules associated with each DP condition are not simply present or absent, but vary from context to context and thus require a more graduated metric in a manner that complicates the process significantly.

Development of a well-constructed fuzzy-set requires a well-thought-out calibration process, as the degree of fuzzy set membership strongly influences the result of the analysis (Basurto and Speer, 2012). Consequently, Ragin (2006) recommends attention to transparency and replicability in the membership and calibration processes. Few sources provide explicit procedural advice on how to transform qualitative concepts to fuzzy values (de Block and Vis, 2018). While Basurto and Speer (2012) and Toth, Henneberg and Naude (2017) offer explicit calibration procedures as a part of their research. Unfortunately, the calibration process in both studies is not suitable for our data because their calibration was predetermined before the data collection, whereas ours takes place after. Further, we require calibration after the fuzzy set is defined. Thus, we turn to Adcock and Collier’s (2001) measurement validity framework and follow the structured calibration procedure set out in Figure 1. We stress that, as indicated by the arrows, this is an iterative process and that care needs to be taken to ensure that the data are well aligned with the theoretical concepts and study objectives.

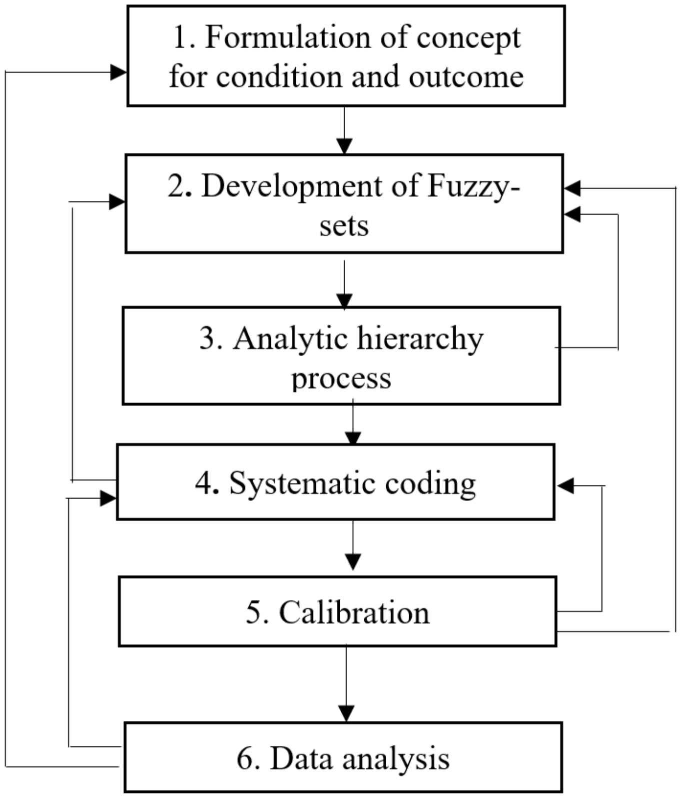


Figure 1: *Scoring, coding and calibration procedure*

In *fs/*QCA approaches, the causal conditions selected and outcomes chosen should be based on prior theoretical knowledge and empirical insights gained throughout the research process (Schneider and Wagemann, 2010). Since our study is based on Ostrom's DPs, we use the concept definitions provided by Ostrom (2010) in Table 1 as the basis for our causal conditions. However, some of these definitions are slightly modified to conform with the irrigation institutions under examination as indicated by the **bold** text in Table 1. For example, consistent with recommended practice (Schneider and Wagemann 2010), we reduced the total number of conditions by joining User Boundary (DP1A) and Physical (resource) Boundary (DP1B) into one condition: *Clearly-defined Boundary*. This was done because, in most of the case studies, user boundary is confined within the physical boundary of the irrigation system. That is, users are typically socially and physically constrained to the extent of the area covered by the irrigation distribution system. The complete list of final study conditions is provided in Table 2.

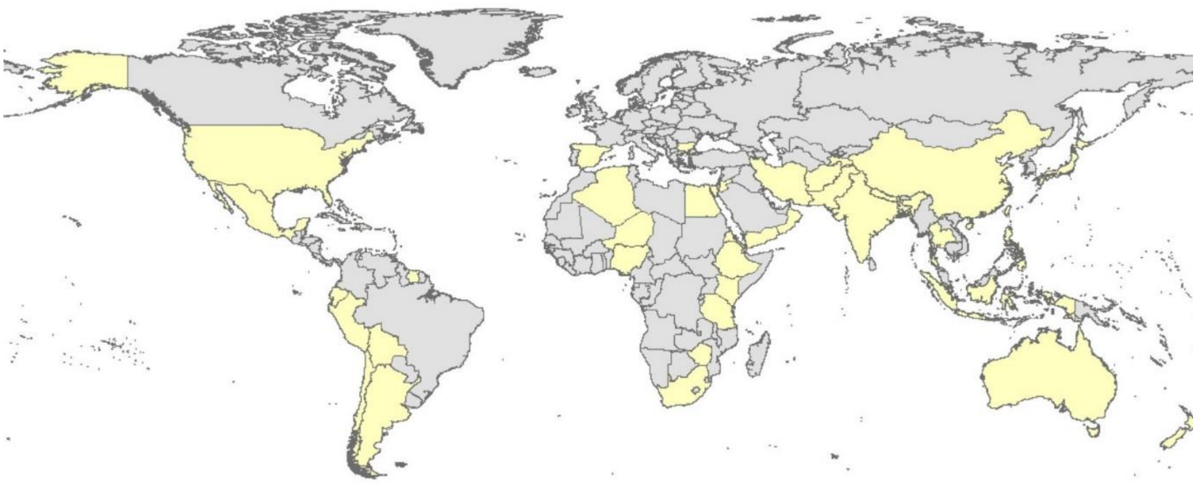
Table 2: *Modifications to Ostrom's DPs for irrigation system case calibration*

Condition (DP)	Definition
1. Clearly-defined boundaries	Legitimate users are clearly defined and identifiable. Physical limits on the extent of the resource are defined at all points in time, and across space.
2a. System congruence with local conditions	Appropriation and provision rules are congruent with local **and system-wide** social and environmental conditions as they change.
2b. Proportional equivalence between benefit and cost	The benefits obtained by water users are in proportion to fixed and system-wide costs of operation.
3. Collective choice arrangements	Most individuals affected by the operational rules can participate in the processes leading up to rule modification.
4a. Monitoring of users	Monitors are accountable to the users **and have the enforcement capacity necessary to ensure compliance with appropriation and use rules.**
4b. **Resource system monitoring**	**System-wide monitoring and reporting exists and is reported to users.**
5. Graduated sanctions	Appropriators who violate operational rules face sanctions, preferably graduated.
6. Conflict resolution mechanisms	Appropriators and their officials have rapid access to low-cost local arenas to resolve conflicts.
7. Minimum recognition of rights to organize	The rights of local appropriators to devise their own institutional structures and rules are not challenged by external government authorities.
8. Nested enterprises	Appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities are organized in multiple layers of nested enterprizes.

3.3. Case selection

The cases for the meta-analysis were sourced from Scopus, Web of Science and Google Scholar using search terms that initially included 'farmers' managed irrigation institution', 'indigenous irrigation institution', 'traditional irrigation institution', and 'water user association'.

To expand the initial list of potential case studies, snow-ball sampling methods were employed. That is, the links and references embodied in the initial articles found were used to source additional material, which continued to other articles that cited the original study via Google Scholar. To reduce any bias that may occur by sourcing only published articles, we followed recommendations provided by Poteete, et al. (2010a) and added all articles including those that had not been peer-reviewed in the database. As a result, we ended up with an initial list of 240 potential case studies that were then screened using two inclusion criteria. First, the case study article had to examine institutional arrangements in detail. Second, where a case study did not provide enough information, we combined two or more articles that discussed the same irrigation institution into one case. In addition, we excluded any case studies that used Ostrom's DPs to evaluate planning processes, and (combined or individual) cases studies that did not contain enough information for further analysis. Figure 2 shows the global scope of the case studies with the number per country listed in the caption to this figure (in parentheses). We ended up with 62 case studies located across 37 countries.



Map Source: Esri (2017)

Figure 2: Case distribution across 37 countries: Afghanistan (1), Algeria (1), Argentina (1), Australia (1), Bangladesh (1), Bolivia (1), Bulgaria (1), China (2), Ecuador (1), Egypt (2), Eritrea (2), Ethiopia (2), Haiti (1), India (2), Indonesia (5), Iran (1), Japan (1), Jordan (1), Kenya (3), Nepal (2), New Zealand (1), Niger (1), Nigeria (1), Oman (1), Pakistan (1), Peru (1), Philippines (2),South Africa (1), Spain (6), Suriname (1), Taiwan (1), Tajikistan (1), Tanzania (3), Thailand (3), United States (4), Yemen, (1) and Zimbabwe (1).

3.4. Development of the fuzzy-set

The preliminary list of sub-sets was derived from best-worst practices typically found in the literature and combined with insights from the case studies (Table A1 of the Appendix). The literature and sub-set of information was then used to develop systematic coding guidelines. After the first round of the coding, we refined the fuzzy-sets and coding guidelines in accordance with the methodology’s recommended iterative process. As discussed above, a combined condition representing *Clear Boundaries* (BOUND) was created to more accurately represent case realities, and to reduce the total number of conditions for the *fs/*QCA. In the case of water governance institutions, we also specified water use rights as clearly defined if i) users have a right to abstract a certain amount of water, ii) the location as to where and when water can be abstracted are specified; and iii) the ways that abstracted water can be used are pre-determined (Meinzen-Dick, 2014). Table 3 provides a list of the final fuzzy-set conditions and outcomes. Table A1 of the appendix lists the scoring guideline that were applied

Table 3: Abbreviation of the DPs that are used in the analysis.

Ten Conditions and an outcome	Design Principle	Abbreviation
Clearly-defined boundaries	DP 1	BOUND
Congruence with local conditions	DP 2A	LOCCON
Proportional COST and benefit	DP 2B	BENFCOST
Collective governance	DP 3	COLLGOV
User monitoring	DP 4A	USERMON
System monitoring	DP 4B	SYSTMON
Graduated sanctions	DP 5	GRADSAN
Conflict resolution mechanisms	DP 6	CONFRES
Minimum right to organize	DP 7	RIGHT
Nested enterprizes	DP 8	NESTENT
Robust institutions	Outcome	ROBUST

3.5. Analytic Hierarchy Process

Transforming the raw case study data into fuzzy-set values always produces some degree of arbitrariness (Skaaning, 2011). To reduce arbitrariness, measurement is needed to translate fuzzy concepts into quantitative scores, that can be subsequently transformed into final fuzzy values. For validity, the measurement criteria need to capture meaningful ideas that accurately reflect the concept being used (Adcock and Collier, 2001). We, therefore, followed the Analytic

Hierarchy Process developed by Saaty (1990) which suggests two-stage pairwise comparisons prior to setting the final fuzzy scores. The first pairwise comparison weights the measurement criteria. The second pair-wise comparison then compares the fuzzy-set based on all criteria. For example, as described by Saaty (1990), if we were buying a house we could first assess each individual option using a common set of criteria, and then secondly (when all houses were evaluated) use those criteria again to compare the full set of purchase options and identify the best purchase choice.

Thus, we first identified a set of criteria to measure the fuzzy-set using information from the literature and substantive knowledge from the case studies. We then translated the DPs into a series of questions that could be used to identify opportunities to increase the robustness of a water institution (Ostrom, 2009). For example, for DP1 we identified four major criteria for clearly-defined user/resource boundaries and water use rights that could be used to increase robustness. Second, we employed the two-stage pairwise ranking of conditions wherein the first stage comparison allowed us to weight each criterion, and the second stage allowed us to determine how much the fuzzy-set complied with each criterion. The resultant pairwise comparison matrixes had a consistency ratio of $CR \leq 0.1$, meaning that the priority ranking of the fuzzy-sets was consistent, and therefore acceptable (Saaty, 2008).

3.6. Systematic coding

Next, a coding system was developed in Nvivo based on the fuzzy sub-sets listed in Table A1of the Appendix. We conducted content analysis on the 62 cases, and each case was coded according to the fuzzy definitions. A memo was linked to a case whose content did not directly comply with the fuzzy-set, but where the meaning was implied throughout the article. In these cases, the data was coded accordingly. The memo also included citation details from other supporting documents to supplement information from the main case study article. Where possible (and necessary) additional information was obtained via personal communication with case-study authors to clarify ambiguous data. All coding was conducted by the first author and, hence, no inter-coder reliability tests were required. In recognition of the fact that this could result in coder bias, however, we developed a set of strict procedures to minimize the risk that this could occur as detailed in the Supplementary Materials to this paper.

3.7. Calibration of the fuzzy-set scores

Using indirect methods of calibration recommended by Ragin (2006), we transformed the initial fuzzy-set score into one of four values. A full membership value of 1 was assigned to a fuzzy-set with the highest score, indicating the most favorable manifestation of the institutional criteria. A membership value of 0 was assigned to fuzzy-set with the lowest scores, indicating the worst manifestation of the institutional criteria. A challenge with fuzzy concepts is that it is difficult to justify the cross over (threshold) point; therefore we did not assign 0.5 values in the fuzzy-sets. Furthermore, cases with maximum ambiguity (i.e. 0.5 fuzzy values) cannot be dealt with in *fs*/QCA analysis (Pahl-Wostl and Knieper, 2014). Instead, with due consideration based on i) our theoretical and substantive knowledge of the empirical studies and ii) the distance in a compliance score between full- and non-member, intermediate scores were assigned based on values of 0.33 which indicated whether a governance arrangement was more out than in; and 0.67 for a governance arrangement that was more in than out (Basurto and Speer, 2012). The fuzzy-set values were then assigned to all cases in the fuzzy data matrix.

3.8. Missing data and the meaning of zero "0"

Out of the 62 cases, there are 46 complete cases, while 16 cases contain missing data mainly associated with the presence or absence of graduated sanction mechanisms (13 cases or 20%) and conflict resolution mechanisms (5 cases or 8%). All missing data were coded initially with a zero fuzzy value that resulted in "0" values in the truth table analysis. However, some of the cases with missing data showed a ROBUST outcome. Therefore, in a subsequent analysis, we chose to explore why the absence (or presumed absence) of these conditions might not have compromised a ROBUST outcome rather than assuming that presence of the condition increases robustness as typically discussed in the literature. Therefore, a "0" value in this study has three meanings, i.e. "truly absent" (when the condition was indeed absent), "not in the set" (missing data: when the condition was not specifically discussed in the case study and is therefore ambiguous), and "not applicable" (which mainly applied to nested conditions. Since most of the case studies were small scale and there was no indication of them being part of a complex or larger institution, we suspect that in most cases graduated sanctions operate – even though there is no mention of them. All of these meanings are identified and explored in the solution path of sufficiency conditions discussed later.

3.9. Data analysis

Finally, we analyzed the data using *fs/*QCA v3.0, developed by Ragin and Davey (2017). Based on Ostrom's views regarding DP lists, the model used for analysis is as follows:

BOUND*LOCCON*BENFCOST*COLLGOV*USERMON *SYSTMON*GRADSAN*CONFRES*RIGHT*NESTENT → ROBUST (1)

The above formula simply reflects a hypothesized combination of DPs that may lead to robust water institutions. Capital letters denote that the conditions and outcomes are PRESENT in an irrigation area. However, unlike a regression equation that would consist of dependent and independent variables, the *fs/*QCA model presents its causal conditions in the left-hand side and the outcome on the right. Further, the process involves Boolean operators as presented in Table 4: logical AND (*) which combines conditions (*set intersect*) to the smallest score, logical OR (+) which joins conditions (*union set*) to the highest score, and logical NOT (~) that signifies the negation of conditions or outcomes (ABSENT) (Ragin, 2009).

Table 4: Description of Boolean operators used in the study.

Boolean operation	Symbol	Description
Logical AND	*	Combine condition (*set intersect*) to the smallest score
Logical OR	+	Join condition (*union set*) to the highest score
Logical NOT	~	Signify negation (absent) of condition or outcome

Finally, Schneider and Wagemann (2012) recommend that study data are first analyzed for necessary conditions before performing any analysis of sufficiency conditions. By necessary, we mean that whenever outcome Y is present, the condition X was also present. To address this requirement, a truth table was constructed from the fuzzy value matrix prior to sufficiency analysis. It contains rows of all possible combinations of causal conditions. We set the value of 1 for frequency cut-off to identify empirical relevant causal configuration, and 0.80 for consistency cut-off to determine which configuration pass the fuzzy-set theoretic consistency in the Quine-McCluskey minimization procedure (Ragin, 2009). We then performed a standard analysis of the truth table for configuration of conditions that are sufficient for robust irrigation institutions.

4. Results

4.1. Necessary conditions

The results of the analysis in Table 5 show the consistency and coverage values are generally high for the presence of DPs in irrigation institutions, suggesting good approximation of set-relations (Ragin, 2006) and the relevance of DPs for ROBUST outcomes. However, only four of the DPs pass the 0.9 consistency threshold value (Skaaning, 2011) for identification as necessary conditions; that is, BOUND, USERMON, SYSTMON, and RIGHT. Of those, BOUND also has the highest coverage value of 0.98 which indicates the relative importance of this condition compared to others. We also tested necessary conditions for failed systems (~ROBUST) and found that only ~BOUND passed the consistency threshold with a value of

0.959 and coverage of 0.870; which is clearly not trivial. This again emphasizes the necessity of clearly defined boundaries for robust irrigation institutions.

Table 5: Analysis of necessary conditions for robust (ROBUST) and failure (~ROBUST) outcome.

ROBUST			~ROBUST		
Condition	**Consistency**	**Coverage**	**Condition**	**Consistency**	**Coverage**
BOUND	**0.949**	0.985	~BOUND	**0.960**	0.871
LOCCON	0.761	0.936	~LOCCON	0.855	0.562
BENCOST	0.862	0.880	~BENCOST	0.672	0.635
COLGOV	0.833	0.897	~COLGOV	0.733	0.612
USERMON	**1.000**	0.889	~USERMON	0.653	1.000
SYSTMON	**0.971**	0.950	~SYSTMON	0.858	0.914
GRADSAN	0.708	0.882	~GRADSAN	0.735	0.474
CONFRES	0.839	0.771	~CONFRES	0.305	0.405
RIGHT	**1.000**	0.889	~RIGHT	0.652	1.000
NESTEST	0.738	0.894	~NESTEST	0.756	0.508

Note: **bold** indicates passing the consistency threshold of 0.9 for a necessary condition.

Next, following a process described in Goertz (2006), we create 2 x 2 tables to search for sufficiency effects associated with the four identified necessary conditions. According to this process, when the bottom right-hand cell (X, ~Y) is equal to zero, a necessary condition is maximally relevant to a sufficient condition. With regard to the DPs for the irrigation institutions included in our study, the results shown in Table 6 suggest that, while all of the necessary conditions identified have important sufficiency condition effects, none of them is sufficient on its own to produce a ROBUST outcome. The bottom left-hand cells (~X, ~Y) show reasonable numbers of observations indicating that necessary conditions are not trivial (Goertz 2006). Interestingly, only BOUND has a zero value in the bottom right cell (BOUND, ~ROBUST) which indicates that the *clearly-defined boundary* DP appears to be maximally relevant as a sufficient condition. However, the presence of two cases in the upper left cell (~BOUND, ROBUST) seems to contradict the necessity finding reported above. The two deviant cases were the Nshara and Mkanyeni canals in Tanzania. In these cases, the users were known but water access and risk sharing were inequitable (fuzzy values of 0.33). Both irrigation systems were managed by ethnic groups with significant power asymmetry that lead to inequity in the rights to use water. However, despite this inequality, the self-governing institutions in question had persisted for many generations. This finding agrees with Agrawal's (2001) observation that hierarchical social arrangements in the distribution of benefits can be sustainable despite inequitable access sharing, such as those of caste systems or areas with ethnic and/or racial inequality. Rohlfing and Schneider (2013) also suggest deviant cases can be the result of under-specification, i.e. omission of the SUIN condition, which stands for a 'sufficient but unnecessary part of a factor, that is insufficient but necessary for an outcome' (Mahoney et al., 2009). This finding supports our decision to examine joined conditions, and we will return to a consideration of that issue after some discussion of parsimonious solutions below.

Table 6: Necessary conditions for robust irrigation system institutions

Table 5a. BOUND

	~BOUND	BOUND
ROBUST	2	41
~ROBUST	19	0

Table 5b. USERMON

	~USERMON	USERMON
ROBUST	0	43
~ROBUST	13	6

Table 5c. SYSTMON

	~SYSTMON	SYSTMON
ROBUST	0	43
~ROBUST	17	2

Table 5d. RIGHT

	~RIGHT	RIGHT
ROBUST	0	43
~ROBUST	10	9

4.2. Analysis of sufficiency conditions

The results of the truth table analysis show there are seven configurations of conditions that are sufficient for ROBUST irrigation institutions, as presented in Figure 3. The notation here follows Fiss (2011) and Ragin and Fiss (2008) who differentiate between core and peripheral or complementary conditions. Core conditions are those that appear in the parsimonious and the intermediate solutions, while peripheral conditions only appear in the intermediate solution (Fiss, 2011). The complete set of truth table results are available in Table A3 in the Appendix to this paper.

Table 7: Parsimonious solutions for ROBUST institutions

Parsimonious solution	Raw Coverage	Unique Coverage	Consistency
USERMON*SYSTMON or	0.971	0.231	0.978
LOCCON*SYSTMON*RIGHT	0.740	0	1.000
Solution coverage: 0.971			
Solution consistency: 0.978			

Figure 3 shows two distinct groups of causal configurations. Group 1 relies on the first parsimonious solution, i.e. the combination of *user monitoring* AND *system-wide monitoring* (USERMON*SYSTMON). The USERMON condition is considered present when monitoring of users has a strong enforcement capacity to ensure rule compliance. The SYSTMON condition denotes that a comprehensive monitoring of water resource conditions and status is in place, and results are accessible to all in a timely manner. These characteristics allow the systems and users to adjust as local circumstances vary. Interestingly, in cases where clear GRADSAN or CONFRES conditions—which are considered important in successful CPR management—are uncertain, USERMON AND SYSTMON conditions consistently appear. The paths that treat GRADSAN as ‘don’t care’ reflect data that may be present or absent in the case study but result in the same outcome. Sufficient conditions that include ~GRADSAN (i.e. absence of *graduated sanctions*) are shared by groups of cases that have either i) high mutual trust within the community (such as irrigation institutions found in Chaisombat, Nishikanbara LID, Shirgin, Tharigat watershed, Ghayl, and Zanjera Danum), ii) high control over water allocation mechanisms (Falaj Al Khatmeen, Nabargram, Sidi Okba), or iii) both. These cases include evidence of minimum conflict and free-rider problems, which may suggest reasons as to why the authors did not discuss this DP in detail—and as such may be coded as missing data in our analysis. However, in the Nishikanbara in Japan and Ghayl in Yemen cases, the authors discuss the role of social norms and mutual trust that prevent users from free riding. All other cases with ~GRADSAN characteristics display failure (~ROBUST) in the outcome.

Conditions	Solution paths for robust institution						
	USERMON*SYSTMON Cov: 0.71; Con: 0.978					LOCCON*SYSTMON*RIGHTORG Cov: 0.74; Con: 1.000	
	1a	1b	1c	1d	1e	2a	2b
BOUND	•	•	•	•	•		
LOCCON	●	●	●	●	●	●	●
BENFCOST	•	•			•	•	⊗
COLLGOV	•	•	•	•		•	•
USERMON	●	●	●	●	●	●	●
SYSTMON	●	●	●	●	●	●	●
GRADSAN			•		•	•	•
CONFRES	•			•	•	⊗	•
RIGHTORG	●	●	●	●	●	●	●
NESTENT		•	•	•	•	⊗	•
Raw coverage	0.520	0.447	0.337	0.433	0.315	0.066	0.080
Unique coverage	0.117	0.029	0.008	0.008	0.022	0.059	0.008
Consistency	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Solution coverage	0.689						
Solution consistency	1.000						

● denotes core condition (present), • denotes complementary or contributing condition (present), ⊗ denotes complementary condition (absent), blank spaces indicate "don't care" situation where a condition could be present or absent. Cov= coverage; Con = consistency.

Figure 3: Sufficient configurations of conditions for robust irrigation institutions (intermediate solution)

Group 2 (2a and 2b) relies on the second parsimonious solution; the combination of *Congruence with local condition* AND *system-wide monitoring* AND *Minimum rights to organize* (LOCCON*SYSTMON*RIGHT) as decisive factors. That is, when users have the authority to self-organize and devise operational rules within a defined framework (RIGHT), they can adapt to various conditions as they change (LOCCON) provided they have required information about relevant resources at the right time (SYSTMON). The solution paths for Group 2 treat the BOUND condition as ‘don’t care’, as the presence or absence of that condition result in the ROBUST outcome. In these cases, the LOCCON condition becomes essential in the configuration. Solution 2a belongs to small communities in Tanzania (Nshara) and Nepal (Raj Kulo and Thulo Kulo) where conflict resolution is missing (~CONFRES). The importance of conflict resolution mechanisms was clearly mentioned in the case study introduction material, but then not discussed in the case study findings. However, Raj Kulo and Thulo Kulo both displayed evidence of having installed devices that tracked water distribution more precisely, as a means to reduce conflict (Martin and Yoder, 1988), while in Nshara furrow irrigators adopted equity and fairness principles to prevent conflict (Gillingham 1999).

4.3. Tests of joined conditions

The results above show that all of the conditions which passed the consistency threshold of the necessary condition analysis were also present in the parsimonious solution paths—except BOUND. However, despite being present in the solution paths for both Groups, which should indicate its' necessity, LOCCON did not pass the original consistency threshold test. This brings us back the issue of SUIN conditions mentioned previously. We hypothesize that both BOUND and LOCCON are SUIN conditions and that their union (BOUND+LOCCON) may reveal whether they are individually unnecessary or insufficient for ROBUST institutional outcomes, but constitute shared rules necessary for ROBUST irrigation institutions. To test this hypothesis, we use the enhanced XY plot (Rohlfing and Schneider, 2013) to determine whether these two conditions can be treated as SUIN conditions. All XY plots were created using *Tosmana* v1.6 (Cronqvist, 2018).

Figure 4a maps the distribution of cases between the BOUND condition and ROBUST outcome to show that, despite being highly relevant with zero cases in Cell 3 (see the centre of figures for cell numbering references), the two deviant cases in Cell 6 contradict the necessity of the BOUND condition as discussed previously. Figure 4b maps the distribution of cases between the LOCCON condition and ROBUST outcomes showing that Cell 1 contains 30 cases which exclude the LOCCON condition from achieving necessity status, notwithstanding it being present in all of the solution paths. This suggests that, consistent with SUIN principles, the presence of LOCCON ensures ROBUST outcomes in cases such as Nshara and Mkanyeni where the BOUND condition is absent. However, the SUIN condition means that cases without BOUND or LOCCON conditions (e.g. Mendoza) will not result in ROBUST outcomes.

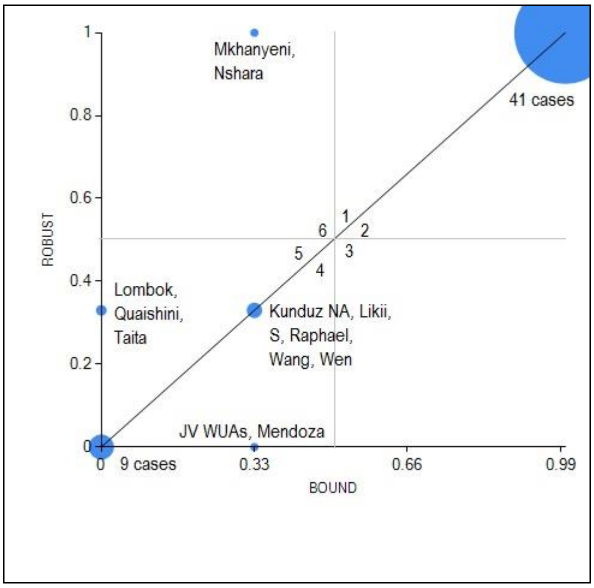


Figure 4a: Enhanced XY plot of BOUND condition

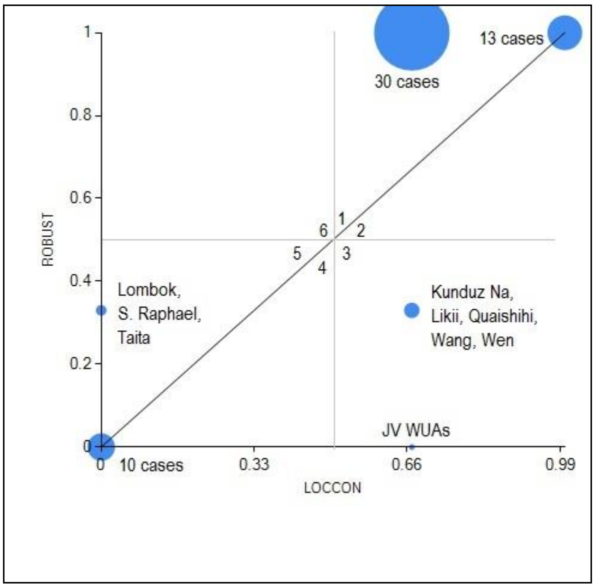


Figure 4b: Enhanced XY plot of LOCCON condition

Unlike the rigid irrigation governance systems in Mendoza, both Mkanyeni and Nshara have flexible working rules for water appropriation including allowing the limited transfer of shares and/or allocation.[1] This allows them to reduce some of the inequality dimension between users, supporting the persistence of the institutions for long periods of time. A direct comparison between these cases might not be appropriate, however, since the irrigation system in Mendoza is larger and more complex compared to the small scale irrigation institutions of Mkanyeni and Nshara. Nevertheless, we consider that comparison is justified on the basis that the three cases were awarded membership in the same fuzzy value category; that is, is more in that out of the BOUND condition, even though they display different outcomes. An additional analysis of the SUIN consistency and coverage values for BOUND+LOCCON reveals a value

[1] In Nshara, temporary transfer took place within the same irrigation system with neighbours or relatives, providing that whoever borrowed or bought water (although selling water was considered illegal) also participated in maintenance activities. To reduce risk and inequality of water access, farmers in Mkanyeni located their plots in different zones. Shared farming during water shortages also took place for the same purpose.

of 0.978, which suggests that the SUIN condition is necessary. The coverage of 0.936 indicates, also, that it is not trivial. Although Figure 5 shows that there are six cases in Cell 3 that reduce the sufficiency effect, it does not contradict the necessary condition evaluation (Goertz, 2006; Rohlfing and Schneider, 2013). This implies that while it is necessary, the SUIN condition alone is not sufficient to achieve ROBUST irrigation system institutions. Figure 5 also shows that there is a deviant case in Cell 1, but the outcome can still be explained by the presence of the condition.

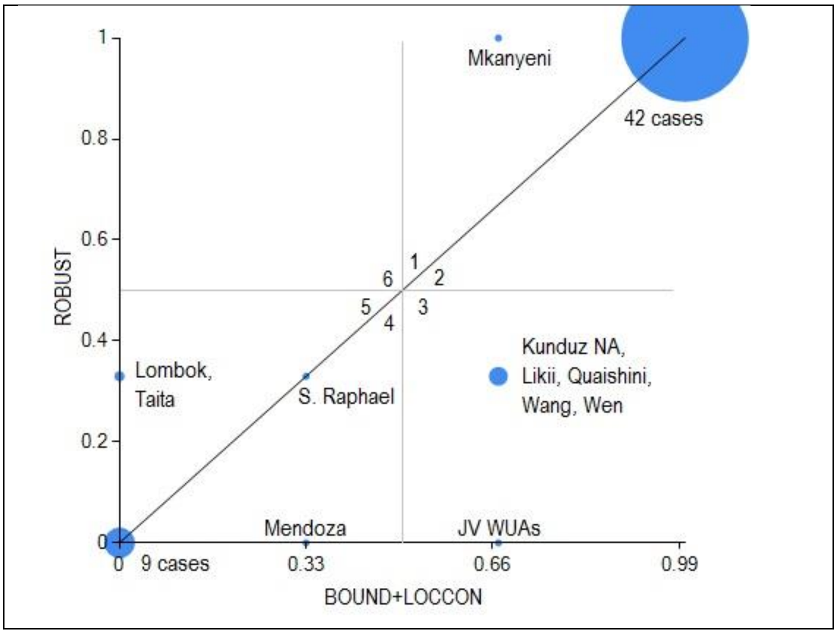


Figure 5: Enhanced XY plot of BOUND+LOCCON conditions

4.4 Sensitivity analysis

One way to test the robustness of fsQCA analysis is to reduce the number of cases (de Bora et al 2016). We, therefore, re-ran the analyses using complete case studies only, to discover that GRADSAN and CONFRES are also necessary for ROBUST outcomes. The result is expected because, as discussed earlier, these two conditions were usually the source of missing data. The test for ~ROBUST also returned consistent results showing that only ~BOUND is necessary. Likewise, the truth table analysis indicates that the parsimonious solutions remained the same, while the intermediate solutions showed only four configurations in Figure 3; that is, 1a, 1c, 1e, and 2b. As a result, we consider that there is no reason to question the reliability of our findings as a result of the presence of some missing data. For further detail, readers are directed to the sensitivity analysis section in the Supplementary Materials.

5. Discussion

The results reported above support Ostrom's view that no list of DPs, if complied with, is likely to be sufficient to ensure institutional robustness. For the irrigation institutions included in the study, however, it has been possible to identify a set of four necessary conditions which increase robustness: these are clearly-defined boundaries, user monitoring, system-wide monitoring, and minimum rights to organize. The seven configurations of conditions that appear to be sufficient for robustness agree with previous studies that have found that not all DPs have to be present in successful CPR management (e.g. Baggio et al., 2016). The configuration of causal conditions is context specific. Our findings are consistent, however, with Ostrom's (2009) view that the presence of more design principles in a self-organizing institution increases robustness. The solution path to 2B, however, needs to be treated with caution as it includes the absence of proportional benefit and cost as a pathway to robustness. Three cases in this group, (i.e. Valencia, Bada Spate irrigation and Mkanyeni) all have full cost recovery but the distribution of benefits was generally inequitable (fuzzy value 0.33). This indicates that calibrating the concept requires treatments of 'more in than out' (0.67), in which the design principle includes the concept of cost recovery that distributed proportionally to the benefit received by the users. In traditional irrigation systems, cost recovery typically is not a major issue as most irrigation infrastructures are built using cheap materials sourced from the surrounding landscape, and are thus easier to maintain with labour and in-kind contribution by the farming community. By contrast, modern irrigation delivery systems may be capital intensive, where the cost of operating and maintaining such systems may not be resolved by in-kind and labour contributions from farmers. This would indicate why low-cost recovery has been a concern for modern irrigation institutions, especially in developing countries (Sampath, 1992).

The results also found two alternative configurations that consistently present in institutions characterized by robustness. As can be seen above, the causal conditions in the parsimonious solutions mirror the necessary conditions except for that of clearly-defined boundaries and congruence with local conditions, which we identify as SUIN conditions (discussed below). Given that this study has highlighted the importance of some DPs including clear user and resource boundaries, rules that are congruent with local conditions, monitoring of both users and the resource system, and local rights to organize—and the relevance of these DPs as alternative pathways to success—we expand upon each of those with some additional examples and detail from the case study materials.

5.1. Clearly-defined boundaries and congruent appropriation rules as SUIN conditions.

In the face of future scarcity and unpredictability, robust water institutions must include property-right structures that are secure yet adaptable enough to support change while providing incentives for users to invest in maintaining the resource and the parts of the system that are under their control (Howe et al., 1986; Quiggin, 1988). Clearly-defined user/resource boundaries and congruent appropriation rules both represent the requisite property rights structure. In our case studies, typical appropriation rules reflect the boundary definition of the resource setting: who gets water, when, where, how much and for what use are the shared rules that clearly and completely define the boundary of the resource system, and at the same time clearly guide the development of working rules that enable efficient and equitable appropriation. Further, all of the ROBUST outcomes cases displayed some degree of security and flexibility in their institutional arrangements. These two characteristics do not necessarily contradict one other; rather the irrigation community usually managed to design shared access arrangements which allowed users to adapt to changes in supply while respecting the assignment of longer-term property rights structures (e.g. annual scarcity pressures can be managed separately from longer-term considerations).

Two types of flexibility are typically discussed in the literature, and appear in the cases. First, Ostrom (1990) emphasizes the congruence of appropriation rules with local conditions where water is allocated in response to the changing water availability either by rotation or turn-taking, reducing water proportionally, or assigning different use priorities under different situations. Second, there may be flexibility in the way that longer-term opportunities to access water can be transferred to other uses or users, or from one place to another, as climate, demographic and economic conditions change over time (Howe et al., 1986). Table 8 provides some examples of the differences between failed and robust irrigation systems.

Table 8: Comparison of failed and robust surface and groundwater irrigation systems

	Failed Systems	**Robust Systems**
Surface water	Kuhl	Tharigat watershed
Access to water	Priority of water in kuhls are given to paddy farmers. (Water use right to kharif is formally registered/ documented).	Ten villages shared water in the Tharigat watershed according to a pre-agreed schedule.
Sharing rules at system level	Clear among kuhls irrigation before new entrants started using water in the upper and middle reaches of the irrigation system.	Clear time sharing and rotation schedule for water allocation for each village.
Source of change in the access to water	New entrant: new rice fields in the upper stream.	New entrant: government takes water from the river in the upper stream to supply drinking water to the nearby city.
Impact or response to change in access to water	Uncontrolled use of water upstream. Useless downstream water rights because irrigation ran dry/system became non-operational.	Water supply decreased significantly. Re-arranged water time sharing and rotation is organised for each village. Proportional reduction of cultivated area.
Surface water	Mendoza	Valencia (Old)
Access to water	Proportional to cultivated area. Water right is attached to land.	Proportional to cultivated area. Water right is attached to land.
Sharing rules at system level	Proportional ownership.	Proportional ownership.
Response to water shortage/ scarcity	Rotation; proportional reduction irrespective of different needs.	Applied different priority in short term, long term and emergency planning based on equity principles; proportional reduction.
Impact on access to water	Unable to respond to scarcity or drought. Increased illegal pumping	Different strategy of water allocation allows the system to achieve efficiency

	by big farmers to augment water supply.	while still maintaining equity principles.
Groundwater	Gnangara aquifer system	Eastern La Mancha aquifer system
Access to water	10-year fixed annual entitlement. The licensing system specified an authorized use or purpose to which extracted water is to be put. Water rights are transferable.	Proportional to cultivated area. Water is attached to land.
Response to water scarcity	Variability of water resource condition is not considered; information on water condition not readily available.	Reduction of abstraction volume per hectare to increase water level in the aquifer as agreed by farmers' association and water authority.
Impact on water resources	Water overdraft, water resource degradation	Water levels still show downward trend but farmers' association and water authority are building a solid institutional framework in which to introduce sustainable practices.

Whichever sharing/appropriation rule mechanisms apply, there are two main lessons that can be derived from the case studies. First, water-sharing arrangements at the system level must be in place prior to the need to change allocation arrangements occurs. Second, while a sense of equity in maintaining user resource sharing in CPR management is important (Quiggin, 1993), in practice the distribution arrangements must be allowed to evolve. Therefore, it is critical to establish individual water use rights that are clearly-defined and difficult to contest. Only by gaining secure access to water will users be willing to invest in the operation and maintenance of the system, and to ensure productive use of the irrigation system resources over time. The case studies also assist us to understand how robust institutions emerge as a consequence of these conditions. Spate irrigation systems in Eritrea (Ghebremariam and van Steenbergen, 2007; Mehari et al., 2005) have existed for many generations despite unequal access to water. Since this irrigation institution relies on access to seasonal floods, water supply is highly uncertain and unpredictable. As a result, complex arrangements for water appropriation are mixed with other social mechanisms to ensure members perceived the rules as fair. This has resulted in continued farmer membership in the resultant CPR collective. Similarly, in Valencia, the irrigation community maintained equality of access through proportional appropriation rules and applied different access priorities as conditions changed to ensure fair access perceptions by users (Glick, 1970; Maass and Anderson, 1978). Alternatively, Barnett et al. (2016) provide evidence of how the application of proportional access in two groundwater-based irrigation systems in Spain became incongruent with the broader economic, social and technological conditions surrounding the system, causing the institutions to fail. This highlights the relevance of local conditions for robust outcomes, and the importance of property rights structures, as suggested by Quiggin (1988), in keeping the appropriation rules congruent with the nature of the characteristics of the physical resource and social demands on it.

5.2. User and system-wide monitoring

The parsimonious solutions in Table 7 show that the raw coverage of USERMON*SYSTMON is comparatively higher than LOCCON*SYSTMON*RIGHT. In addition, it has a unique coverage of 0.231 which shows that around 23% of the cases can be explained by this solution alone, without the need for others. Based on these two features, the USERMON*SYSTMON solution may, therefore, be considered more important than the LOCCON*SYSTMON*RIGHT solution. However, it is important to note that the concept used for monitoring users and resources in our systematic coding was slightly different to that of Cox et al. (2010). While separating monitoring of users (DP4A) from the monitoring of resources (DP4B) in their modified DPs (see Table 1), Cox et al. (2010) suggest that they indicate the presence of monitoring for both users and resources in DP4A, while DP4B indicates any accountability of the monitors in the institutions.[2] The same approach was used by Baggio et al (2016). In our view, keeping the two monitoring types included in DP4A separate (as in Table 1) is beneficial in helping to search for and find ways of increasing the

[2] "*Principle 4A stipulates the presence of monitors, whereas 4B stipulates the condition that these monitors are members of the community or otherwise accountable to those members*." (Cox et al 2010: *Principle 4: Monitoring*). However, the authors reviewed the importance of environmental monitoring for adaptation.

robustness of irrigation institutions. In our view, combining the monitoring of individual user behavior with the benefits of reporting on the status of the entire resource is about two separate issues that run the risk of being ignored by researchers when investigating CPRs using Ostrom's DPs.

In support of this view, we found evidence of such oversight in some of the case studies. In the case in Kenya (Likii WRUA) and two cases in China (Wang and Wen villages), for example, the authors clearly identified the presence of monitoring (focusing on users and the status of use), and that the monitors were accountable to users. However, despite the presence of all DPs according to the authors, they observed significant inequality between users (in all cases), difficulties in coping with changed socioecological conditions (Likii WRUA), and over exploitation of water resources (Wang and Wen villages). These three cases indicate two important points: i) there can be a lack of enforcement despite the presence of accountable monitors and monitoring the users/resources, and ii) if resource monitoring does not exist, or the information cannot be accessed in a timely manner to adapt to the social-ecological change, failure is more likely. We coded these three systems as 'fragile'. In addition, the comparison of two groundwater-based irrigation institutions in Table 8 indicate how monitoring of, and timely available information on, resource conditions clearly contribute to robust institutions. Therefore, establishing an effective individual use monitoring system is important so that aspiring, but ineligible, users can be excluded and that allocations, once made, are complied with.

Different from other types of CPR where failure of the system tends to impact all resource users in the same way, often weak water institutions involve adverse unidirectional impacts where the actions of upstream users can impose unfair and socially inefficient impacts on downstream users – especially during short-term water scarcity. This is particularly evident in the three 'fragile' cases mentioned above. Separate system-wide monitoring should ensure equitable sharing of the available resource. At the broader level under effective enforcement rules, eligible downstream users are able to exercise their rights while not violating others; thus preventing infringement upon the common property resource. Further, resource monitoring is essential for effective planning and decision-making in natural resource management contexts (Babu and Reidhead, 2000). Finally, the flexible appropriation and provision rules discussed above depend on timely information from the monitoring process, which will inform the need for the system and users to adapt to various conditions as they change. In support of this conclusion, all of the FAIL cases in this study had no proper monitoring systems in place, nor was use infringement or system condition information easily accessible in a timely manner.

5.3. Combining congruence principles, system-wide monitoring and the right to organize to aspire adaptive capacity

As outlined above, water is unique compared to other types of natural resources as it tends to flow from upstream to downstream, with sequential use and re-use values and extremes in terms of quantity, quality and time of impact (Hanemann, 2006). It has destructive power during floods or can create severe competition in a long drought. These features make water management more challenging, especially where management requires rapid adaptation. The second parsimonious solution which combines congruence of appropriation and provision rules with local conditions, system monitoring and the minimum right to organize (LOCCON*SYSTMON*RIGHT) represents a pathway to increased adaptive capacity, and through this system robustness. Consistent with acting upon the information provided from an effective monitoring system, institutional success necessitates active group management with the authority to hold members in check over their use of system resources (Bromley, 1992). Most importantly, these arrangements must also be capable of responding to dynamic changes in economic, social and environmental conditions at particular times and places as rapidly as these changes occur. To achieve rapid adaptation, authority appears to be best left with the local users/managers since they are more familiar to the local context and directly face the immediate changes or problems (Cundill and Fabricius, 2009) but these authorities need to be nested within robust system-wide structures.

In all irrigation systems, the minimum information required typically includes access to continuously updated information on the quantity of water available for irrigation so that the community and individuals can plan for water allocation and use, and, also, maintain infrastructure in a timely manner. The more complex the irrigation delivery system and generally the larger it is, the more important system-wide monitoring. Table 8 shows how robust institutions make use of information to respond and adapt to various changes in condition including how they adjust the working rules to maintain congruence with local conditions over time (as discussed earlier). By comparison, in institutions where information paucity prevents timely adaptation and response to socio-ecological change, or where links to larger irrigation systems outside of operating boundaries prevent local modification of operational rules (e.g. the Kuhl case study), institutional decline or failure is the typical outcome. Our finding that RIGHT design principles constitute a necessary condition for robust outcomes is highly consistent with these outcomes. Local decision-making, however, is only part of the solution; there is a need to also incorporate wider political, economic and environmental information into the local decision-making process and prevent resource users in one part of the system having impacts on other parts of the system in a manner that is inconsistent with agreed system-wide rules. That is, the right to organize locally should not compromise the shared rules at the system level.

5.4. Proposed design principle modifications

Our analysis of 62 irrigation systems corroborates Cox et al.'s (2010) conclusion that Ostrom's DPs are well supported by empirical evidence. In this study, the *fs/*QCA approach proved useful for examining institutional arrangements with respect to each of the design principles in more detail; it allowed us to identify certain necessary conditions and alternative configurations of causal conditions that could lead to robust irrigation institutions. Based on this analysis, we are in a position to suggest some further irrigation-system focused modifications to Ostrom's DPs (Table 9) with respect to ongoing congruence (DP 2A), the linking of monitoring to enforcement arrangements (DP 4A), and the clearer reporting responsibility by system monitors to system users—rather than monitoring alone that could be applied to other irrigation CPRs as a test of their usefulness more generally.

Table 9: Proposed further modifications to Ostrom's DPs for broad application

	Three DPs as listed in Ostrom (2010)	Modified DPs based on the comparative analysis
2A.	Congruence with Local Conditions: Appropriation and provision rules are congruent with local social and environmental conditions.	Congruence with Local Conditions: Appropriation and provision rules are congruent with local **and system-wide** social and environmental conditions as they change.
4A.	Monitoring Users: Individuals who are accountable to or are the users monitor the appropriation and provision levels of the users.	Monitoring Users: Monitors are accountable to the users **with enforcement capacity necessary to for ensuring compliance with agreed appropriation and use rules**
4B.	Monitoring the Resource: Individuals who are accountable to or are the users monitor the condition of the resource.	**System-wide monitoring: System-wide monitoring and reporting exists and is reported to users in a timely manner.**

Consistent with Ostrom's desire to test theory with empirical data in this space, we, therefore, offer these modifications for application and testing by scholars whose work aims to increase the robustness of irrigation institutions. We would be interested to see tests of necessity and sufficiency in other CPR settings to determine any common DP conditions or the identification of additional alternative solution pathways. Such research would bring us closer to the objectives set out by Ostrom for determining if the DPs continue to stand the test of time—as we hope future water governance institutions will.

6. Concluding Comments

The design of water governance and allocation systems remains an art and, while many get to write about opportunities to improve them, very few people are invited to participate in their renewal; especially when the necessary changes involve the significant re-specification of the processes and institutional arrangements that determine who gets access to water. Moreover, in the real world of water governance and allocation, there is an immense amount of detail that never gets written down. Our aim, however, was to search for insights that can be used to convince communities that the current suite of institutions used to manage their water resources are flawed, can be fixed and, if fixed, will help to deliver prosperity. The collection of evidence from many case studies across a substantial number of countries is one way of doing this. The results, which emerged from a careful examination of a fuzzy set of data, identified a) four necessary conditions; b) seven solution path configurations; and, perhaps more importantly, c) a union of conditions that, when absent, are likely to result in system failure during times of stress and/or when demands for access are shifting.

The approach taken attempts to deal, as objectively as possible, with the need for concrete advice in a world where, at best, the concepts are fuzzy and situation specific. We have aimed, as objectively as possible, to come up with a suite of recommendations that could assist in the transformation of failing systems into ones that could confidently be described as robust, and also for changes that can be made in order to ensure that systems which are currently performing well continue to do so. That is, we aspire to the development of institutional arrangements that those reliant upon the system's water resources can be confident will serve them well, especially in times of stress and as new demands emerge. The recommended modifications of three of Ostrom's DPs add a new temporal dimension to her work; emphasis on the importance of attending to appropriation arrangements designed to facilitate change and, also, stressing the importance of monitoring both system-wide and individual use conditions.

Our suggested modifications also identify a need to understand how design principles interact with one another. Robustness is enhanced by arrangements that, for example, understand the interdependence of monitoring at different scales, allocation arrangements and enforcement capacity.

Finally, the research reported here is reliant on the development of analytical techniques that seek to reduce arbitrariness. All the judgements made are summarized in the Appendix and Supplementary Material attached to this paper. When it comes to methodology, the highly skewed nature of the data collected suggests a need for more fine-grained analysis. At the moment, the best that we can do is identify relationships among broad, very fuzzy, concepts. Much more research is needed, for example, on concepts like "enforcement capacity;" "appropriation and use rule" options; and ways to ensure that "appropriation and provision rules are congruent with current, and flexible enough to cope with future, local social and environmental conditions."

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