Improving the Robustness of Water Management in Indonesia

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Verily, all praise is for Allah, we praise Him and we seek His assistance and we ask for His forgiveness. And we seek refuge in Allah from the evils of ourselves and from the evils of our actions. Whoever Allah guides, there is no one that can lead him astray, and whoever is led astray, there is no guide for him. (The Prophet Muhammad, peace be upon him; from the sermon of necessity).

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Declaration

I certify that this work contains no material which has been accepted for the award of any degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and, where applicable, any partner institution responsible for the joint-award of this degree.

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Publications arising from the thesis

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Conference presentation

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Abstract

The study of the irrigation system as a common property resource has been well documented. Most of the irrigation systems that survive for generations enjoy relatively uninterrupted use of water. The present, however, is no longer the same as what it was hundreds or, even, fifty years ago. Today, there is intensifying many more direct and indirect socio-economic driving forces put water resources under pressure. This calls for more suitable water resource development and management systems. This study sought to find answers to the following questions:

1) Are there plausible water management options that could maintain agricultural systems and rural economies, without constraining water for the development of other sectors?

2) What set of institutional arrangements would enable efficient and equitable use of water?

Using these questions to guide the research agenda, this thesis uses Common-Pool Resources (CPRs) theory and, in particular, the eight design principles (DPs) for the development of robust institutions proposed by Elinor Ostrom in 1990. The results are presented in three analytical chapters.

The first analytical chapter seeks to identify a set of necessary and sufficient conditions for the development of robust institutional arrangements for the management of irrigation. Using a meta-analysis of 62 irrigation case studies across 37 countries, the data was analyzed using fuzzy-set Qualitative Comparative Analysis (fs/QCA). The results show that out of the eight principles, four are necessary conditions for a robust institution, i.e. 1) Clearly defined boundaries; 2) Monitoring of user with enforcement capacity; 3) System-wide monitoring of resources; and 4) Minimum rights to organize. The results also identify two minimum configurations that appear to be sufficient. The first configuration involves a combination of

user monitoring AND *system-wide monitoring arrangements.* The second involves a combination of *congruence with local condition* AND *system-wide monitoring* AND *minimum rights to organize*. Based on the findings, a modification of three of Ostrom's design principles is proposed so that the principles take fully account of the characteristics of water resources.

The resultant modification Ostrom's DPs is applied in the second analytical chapter. This chapter aims to examine the role of Water User Associations (WUA) in Southeast Sulawesi Province, Indonesia. The research collected data from a series of interviews, a stakeholder workshop and six focus group discussions in three regencies of the province. The study resulted in propositions for sustainable irrigation system institutions in Southeast Sulawesi and Indonesia in general. In addition, the prepositions signify the need for hierarchical arrangements to foster the emergence of locally defined solutions of collective action problems in managing the common irrigation system.

The third analytical chapter focuses on the development of guidelines for the nesting of local management arrangements within broader hierarchical arrangements which typically are examined last in any discussion that seeks to use Ostrom's Design Principles. Turning this approach on its head, the analysis undertaken begins by putting Ostrom's nested principle first. to examine a complex, and large-scale CPR system, with heterogeneous values and uses. By putting the nested principle first, a new perspective emerges. In particular, the user is forced to accommodate the other principles within a hierarchy. In fairness, Ostrom acknowledged is that this was necessary but she did not propose a way to do it. Taking her advice literally and to test it this third chapter puts her last principle first – rather than last – and then searches for ways to apply her other principles within a suite of hierarchical institutional arrangements developed for river basin management in the province of Southeast Sulawesi. The resultant analysis makes use of the data from the previous chapter, in addition to the review of regulations, existing basin plan documents and relevance studies in the period of the first water law promulgation.

That is, Ostrom's design principles are combined with a transaction cost analysis. In the basin examined, the results show that existing institutional arrangements are not sufficient and, indeed, prevent users from adapting to foreseeable future changes in a manner that is efficient and equitable. Further, the analysis finds that the hierarchical structure of the extant institutions do not align with the complex nature of water resources in the province. The resultant analysis developed a list of gaps which, if addressed, would improve prospects social and economic development while keeping use within sustainable limits.

Based on all the analysis, the thesis closes in a final summary chapter with a suggested modification of Ostrom's design principles and a set of policy recommendations for consideration by Indonesian water managers and water users.

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List of Abbreviations

ADB	Asian Development Bank
BJPSDA	Biaya jasa pengelolaan sumber daya air (water service fee for commercial purposes)
BPSDA	Bidang Pengelolaan Sumber Daya Air (Water Resource Management Agency)
BWS	Balai Wilayah Sungai (River Basin Organization)
CPR	Common Pool Resources
DGWR	Directorate General of Water Resources
DP	Design Principle
FAO	Food and Agricultural Organization
FGD	Focus Group Discussion
IMT	Irrigation Management Transfer
IOMP	Irrigation Operation and Maintenance Policy
MPW	Ministry of Public Works
OECD	Organization for Economic Co-operation and Development
P3A	Perkumpulan Petani Pemakai Air (WUA)
RBO	River Basin Organization
UUD 1945	Undang-Undang Dasar 1945 (Indonesian Constitution 1945)
WATSAL	Water Sector Adjustment Loan
WS	Wilayah Sungai (river basin or basin territory)
WUA	Water User Association
WRL	Water Resource Law

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Chapter 1: Introduction

It is more appropriate to say that the state's power lies on its authority to create rules for the economy to function, a rule that forbids the exploitation of the weak by those who own capital. (Mohmmad Hatta, the Founding Father of Indonesia; cited in Al-Afghani, 2016)

1.1 Research background and motivation

The study of irrigation systems as common property resources has been well documented. Most of the irrigation systems that have survived for generations enjoy relatively uninterrupted use of water. However, present-day conditions are no longer the same as those of hundreds, or even fifty, years ago. The intensification of competing demands from a variety of direct and indirect socio-economic drivers puts water resources under pressure (Turner, 2004). Because agriculture is the primary water user, capturing more than 70% of the world's freshwater, its allocation is currently under scrutiny. Even in a water abundant country, seasonal variability and uneven spatial distribution of water create the problem of water not being available in the right place and/or at the right time (Hanemann, 2006; Turner, 2004). As demand outgrows supply, reallocation from surplus to deficit regions, or from agriculture to other sectors, has become the norm. However, when a transfer takes place without the proper support of appropriate institutional arrangements, it may have harmful effects on communities that are deprived of access to water, and generate resistance to change.

Evidence suggests that reallocating water from agricultural to non-agricultural uses has the potential to result in significant negative impacts for agricultural and rural livelihoods (Komakech et al., 2012; Meinzen-Dick and Ringler, 2008; Rosegrant and Ringler, 1998). For households, whose livelihoods depend on natural resources (i.e. agricultural farmers reliant on limited water supplies), this may cause loss of livelihood and assets, which may lead farmers into poverty (Cook et al., 2009). Negative outcomes may also accrue to urban water users where transfers from agricultural uses to cities may be undertaken without first understanding the needs of domestic water users, and thus disrupt farmer's access to water and livelihoods for little gain (Komakech et al. 2012). Birkenholtz (2016) agrees, finding that farmers often resist water being reallocated to cities and industries, especially when farmers experience material losses while lacking support or recompensate to other livelihoods alternatives from the state.

However, the requirement for water to increase agricultural production to feed growing populations, while not constraining water supply to other sectors including that required to maintain ecosystem services, is a challenge shared by many countries. The proposed solution often calls for more suitable water resource management which focuses on institutional design solutions rather than engineering projects (Ostrom, 1993). Focusing on augmented supply from the construction of more dams or storages will only buy time in many contexts; eventually, demand management will need to be put in place (Young, 2019). Further, this challenge is not limited to arid and semi-arid countries; it also applies to tropical rain forest countries, like Indonesia.

1.2. Water, irrigation and rice policy: Indonesian context

For many years, Indonesia has depended on the agricultural sector for national food security, and in particular rice production. Approximately 77% of Indonesia's farmers produce rice on average landholdings of less than one hectare (ADB 2016). Irrigated rice cultivation has a long history, dating back to the fifth century in Java and Bali, and while the traditional rice-irrigation systems in Java eroded during the colonial era (Van Setten Van der Meer, 1979), Bali's *Subak* system of collective governance persists to this day.

In Indonesia, the first modern irrigation system was introduced in Java by the government of East Indie (the colonial government) in 1830 (Booth, 1977a; Ravesteijn, 2007). The irrigation development was initially intended to support sugar cane, one of the export crops that was forced to cultivate by the colonial government during the Cultivation System period from 1830 to 1870 (Booth, 1977a; Ertsen, 2006; Ravesteijn, 2007). The technical inadequacies of village-based small-scale irrigation systems were inappropriate for large estate cultivation (Booth, 1977a). Thus, modern irrigation technology was started and took place on both the already existing indigenous system and the newly built irrigation network (Horst, 1996). Only after the widespread of famine in *Demak* and *Grobogan* regencies in 1948-1950, the government of East Indie started to support wet rice farming in the irrigation development project (Ersten 2006; Ravesteijn 2007).

The importance of irrigation development was emphasized during the first three decades of the twentieth century. It was aimed to increase rice production which was considered to be a determinant factor of people's welfare in Java (Booth, 1977a; Van Oosterhout, 2008). However, this irrigation enthusiast was later criticized and viewed as less effective and even seamed to lead to a decrease in productivity (Van Oosterhout, 2008). As noted by Booth (1977a), rice yields in Bali and Lombok, where the government had not initiated any irrigation project, were significantly higher than those in Java. Likewise, in North and West Sumatera where irrigation controlled by Public Works was relatively small, it was also reported to have higher yields (Booth, 1977b). Further, Booth (1977a) concluded that the colonial government expenditure on irrigation development had little effect on the level of people's welfare in Java.

After Indonesian independence in 1945, irrigation development continued at a slower pace. It focused on infrastructure in Java and outer islands. However, deferred maintenance had caused deterioration of irrigation works left from the colonial period. It resulted in a

50% drop in the irrigation canal average capacity, which further caused declining of irrigation coverage area (Booth, 1977a). Thus, during the first two decades following independence, Indonesia experienced a continuous shortage of food (van der Eng, 2014). The limited stock of rice, insufficient foreign exchange for imports, and more than 300% spike in the price of rice contributed to a crisis in 1966 (Mears, 1984). Only after the crisis in 1966, Indonesia started to receive food aid and continued for several years due to local famine in Central Java and Nusa Tenggara (van der Eng, 2014). Therefore, it is not surprising that Indonesia's general development objectives have been closely linked to rice policy (Mears, 1984).

To secure the country's food supply, rice self-sufficiency has always been a target of Indonesia's development since *Repelita I* (the Five Year Development Plan) from 1969/70-1973/74 (Mears, 1984). The state-led irrigation development strategy focused on rehabilitation, expansion, and construction of new irrigation schemes and system operation and maintenance (Oad, 2001). The Plan arrangement ultimately achieved rice self-sufficiency in 1984. The policy persists, but its outcome is no longer quite as successful. A lack of water supply has been identified as a principal constraint to further rice area expansion and intensify rice production. This argument has reinforced the dominance of physical construction for irrigation development (Oad, 2001; Sumaryanto, 2012).

The problem of the construction-oriented development, however, was apparent during the financial crisis due to the fall of oil prices in the mid-1980s (Bruns 2004). The focus on new infrastructure development has neglected the routine maintenance, and the performance was below expectation (Oad, 2001; Bruns 2004). By 1987, the Indonesian government had issued an Irrigation Operation and Maintenance Policy (IOMP), primarily aimed at encouraging better management of irrigation systems by transferring management of small-scale irrigation systems to water user associations [WUAs] (Bruns, 2004; Oad, 2001). Limitations in the IOMP and its outcomes, however, led to another set of reforms and the release of Presidential Instruction Number 3 in 1999 in response to concerns raised by the World Bank through their Water Sector Adjustment Loan (WATSAL). This new set of reforms again focused on improved irrigation institutions, empowering farmers to be decision-makers, and encouraging them to take more responsibility for the operation and maintenance of local irrigation systems. Nevertheless, transfers of responsibility to farmers/WUAs via the Irrigation Management Transfer (IMT) in 1999 have not improved the performance of irrigation institutions as hoped. This is partly due to a lack of capacity by farmers/WUAs to perform their new role successfully, and conflicting interests with irrigation agencies that control the irrigation development agenda and prefer large construction projects to local maintenance (Bruns, 2004; Suhardiman and Mollinga, 2012; Vermillion et al., 2000). More recently, persistent problems with irrigation institutions have been further complicated. The requirements to secure water to support the long-standing policy of rice self-sufficiency is being challenged by the emergence of competing demands for water by non-agricultural sectors such as tourism, mining and growing urban demand. It is expected that further reforms will thus be needed.

1.3 Sustainable irrigation under a competing demand for water

In Indonesia, water is currently considered sufficient to meet population and economic growth demands (Piesse, 2016). Data from ADB (2016) shows the total water availability in Indonesia is 690 x 10^9 cubic meters per year, while the demand is 175 x 10^9 cubic meters per year. Despite this, DGWR (2003) acknowledges that an imbalance between demand and supply is one of the main constraints on economic development. This is due to the fact that unequal spatial distribution of water resources, annual and seasonal variation in rainfall, poor water management, limited infrastructure, environmental degradation, and adverse climate-related issues increasingly contribute to localized water scarcity in Indonesia (Piesse, 2016; Sumaryanto, 2012).

At present, most water withdrawals accrue to agricultural users; the sector accounts for 81% of total water use, while the remaining water is allocated to industry (7%) and municipal (12%) users (Figure 1.1, FAO 2012). However, DGWR (2003) estimates that, by 2020, demand from industry and municipalities will increase in total between 25% and 30%. Since total water resources are ultimately limited, this will require some form of water reallocation from agriculture to industry and municipal users, especially during dry seasons (DGWR 2003; FAO 2012).

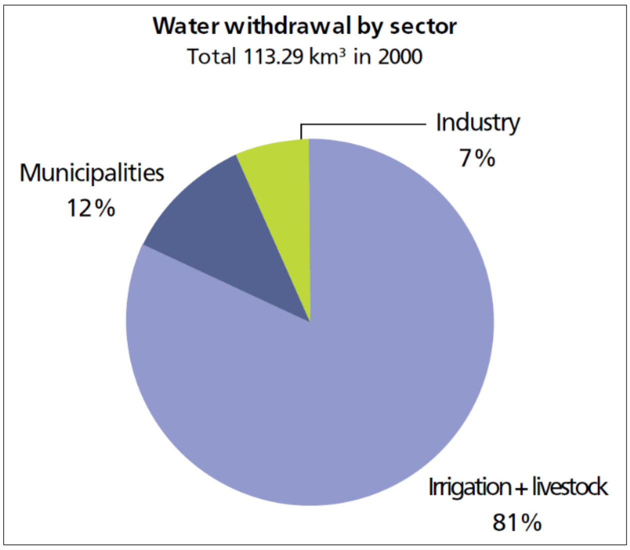

Figure 1. Water withdrawal by sector (Source: FAO 2012)

Competition over water resources is already occurring in some parts of Indonesia. For example, Kurnia et al. (2000) describe how competition over water resulted in conflict within farming communities, and between farmers and factories in West Java. In these examples, reallocation of agricultural water to industrial factories was facilitated via permits issued by the Indonesian Mines Agency, on behalf of the central government. However, since the factories often needed large quantities of water, which often exceeded the volume of water granted to them by the Agency permits, many sought ways to gain additional water resources. Some acquired water by buying or renting agricultural fields with access to irrigation water. This form of water right transfer was not a formal part of the irrigation system, but was usually accepted by local farmers. However, other factories acquired additional water illegally, and/or took water out of turn (i.e. ahead of other users). As a consequence, due to the poor institutional arrangements, farmers often lost their harvest and income.

In Bali, there are additional examples of how current water management arrangements have failed to address water scarcity, resulting in the overexploitation of water resources and inequitable water allocations. According to Cole and Browne (2015), interactions between highly diverse water use groups, coupled with weak governance systems and the economic power of the tourism industry, has led to a deterioration of water resources and inequitable water allocation. Feedback structures that should monitor for such outcomes, and trigger change in response, are either absent or underdeveloped and the governance system therefore does not respond to inequitable allocations. Cole (2012) reveals how water appropriation for the tourism sector is favored because 80% of Bali's economy depends on this industry. He reports that a new reservoir constructed in the *Tabanan* area specifically for irrigated rice farming had more than 50% of its water reallocated to the tourism sector. As a consequence, conflict now regularly occurs between the *Subak* managers (a traditional institution that manages water for farming) and local villagers who have sold their land and water assets to tourist developments or bottled water companies (Cole, 2012). Conflict typically results from the fact that water is scarce due to these historic sales, and that negatively impacts smallholder farmers who depend on agriculture for their livelihoods (Strauß, 2011).

These examples signify the need to evaluate the institutional arrangements of water resource development in Indonesia. A set of reforms are required that can minimize current impacts on agriculture and smallholder farmers, and capable of responding to dynamic change in the future. Fortunately, this is an ideal time for such an examination of Indonesian water management arrangements. The Indonesian government has previously undertaken broad reforms to improve national water policy (Sarwan et al., 2005), resulting in the implementation of the 2004 Water Resource Law (WRL) No. 7 as a regulatory framework. That Law covered all aspects of management, as well as conservation and infrastructure, and allowed more scope for public participation in managing water resources (Al'Afghani, 2006). Another important aspect of the Law was that it defined water use rights, and how these rights were to be exercised (Sarwan et al., 2005). However, in February 2015, the Law was cancelled by the Constitutional Court because it contradicted Article 33 of the Indonesian Constitution – (UUD 1945). After four years of discussion and negotiation in Parliament, a new WRL was passed and promulgated in October 2019. The main feature of this new WRL is an emphasis on the public's right to water. This includes, in order of priority, meeting people's daily needs for water, the needs of smallholder farmers, and the needs of the public water supply system. Once higher priority uses are satisfied, and if there is surplus water available, lower priority water resources can be allocated including non-commercial public uses and, lastly, license-based commercial uses. However, the method by which the state can secure water for these prioritized uses, while simultaneously balancing social, economic and ecological functions of water as required by the 2019 WRL, remains uncertain.

1.4 Research questions

This thesis is therefore undertaken to evaluate the institutional arrangements that govern water resource development in Indonesia and to consider how they can be improved to address future challenges in water supply and demand. Considering its priority status as a primary water user, and its role as a major player in the Indonesian economy, the study has a deliberate focus upon the agricultural sector. In particular, the research is aimed at answering the following questions:

1. Are there plausible water management options that could maintain Indonesian agricultural systems and rural economies, without constraining water availability for the development of other sectors?
2. What set of institutional arrangements would enable the most efficient and equitable use of water in Indonesia?

1.5 Research Objectives

Using the above questions to guide the research, the research objectives are defined as follows:

1. To investigate necessary and sufficient conditions for institutional arrangements that promote robust irrigation systems.
2. To investigate whether institutional arrangements at the local level are capable of dealing with future uncertainty and changes in water availability.
3. To search for possible alternative institutional arrangements to govern water resource development in Indonesia, and the processes needed to create the capacity of the governance systems to properly manage water.

1.6 Overview of the research design and data collection methods

Since the main topic of the thesis is institutional design, common-pool resource (CPR) theory and the eight design principles for robust, self-governing institutions proposed by Elinor Ostrom in 1990, form a basis for the work. To achieve the research objectives, work was conducted in three phases: 1) a global comparison of irrigation case studies, 2) a case study of a local irrigation system, and 3) an investigation of regional river basin management.

To define the necessary and sufficient conditions for robust irrigation institutions, it was determined that a suitable methodology involved a combination of meta-analysis and fuzzy-set qualitative comparative analysis (fs/QCA). The meta-analysis was used to synthesize data from existing case studies, while the fs/QCA was used to establish causal conditions that effectively link the design principles to the outcome, which is robust institutions. The meta-data from case studies were gathered first from Web of Science and Scopus databases, using the following keywords: ‘farmer-managed irrigation’, ‘indigenous irrigation’, ‘traditional irrigation’, and ‘water user associations.’ Two criteria were used to decide on the inclusion of an article: 1) the case study must have examined the institutional arrangements in detail, and 2) two or more materials that discuss the same irrigation system were combined into one case study. Snowball sampling was used to extend the initial list of potential case studies; references cited in the case studies and other articles that cited the case studies, noted by Google Scholar, were included. Following Poteete et al. (2010), non-peer reviewed articles were also included. These inclusion criteria resulted in the inclusion of sixty-two irrigation system case studies, conducted in thirty-seven countries around the globe.

The second and third parts of the thesis were based on a case study of Indonesia's Southeast Sulawesi Province. The use of the case study method was justified since the study of institutions requires an in-depth investigation of this phenomenon within its real-world situation (Yin, 2018). The province was chosen for several reasons: 1) It is located in eastern Indonesia, which is an area that is considered to lag behind the country's western provinces, 2) The province has seen rapid growth of the mining sector and commercial agriculture (palm oil plantation), which both use the water resources, traditionally used for rice production, 3) The province has experienced environmental and water quality issues due to mining activities and land clearing for palm oil plantations, 4) There were ongoing multipurpose dam projects to support various water uses in the province, and 5) It has witnessed continued urban development.

Data for the case study were collected using qualitative approaches. To understand the contexts and institutional arrangements of irrigation systems and water management in the province, I integrated data from various sources: 1) interviews (with government officials at different levels of water management, officials from the agriculture department, village heads and head of a water user association federation), 2) six focus group discussions, and 3) a stakeholder workshop. For the third part of the analysis, a study of relevant key documents and literature were included. This range of data sources served as a form of data triangulation (Yin, 2011). The overall research design is presented as a research roadmap in Figure 1.1.

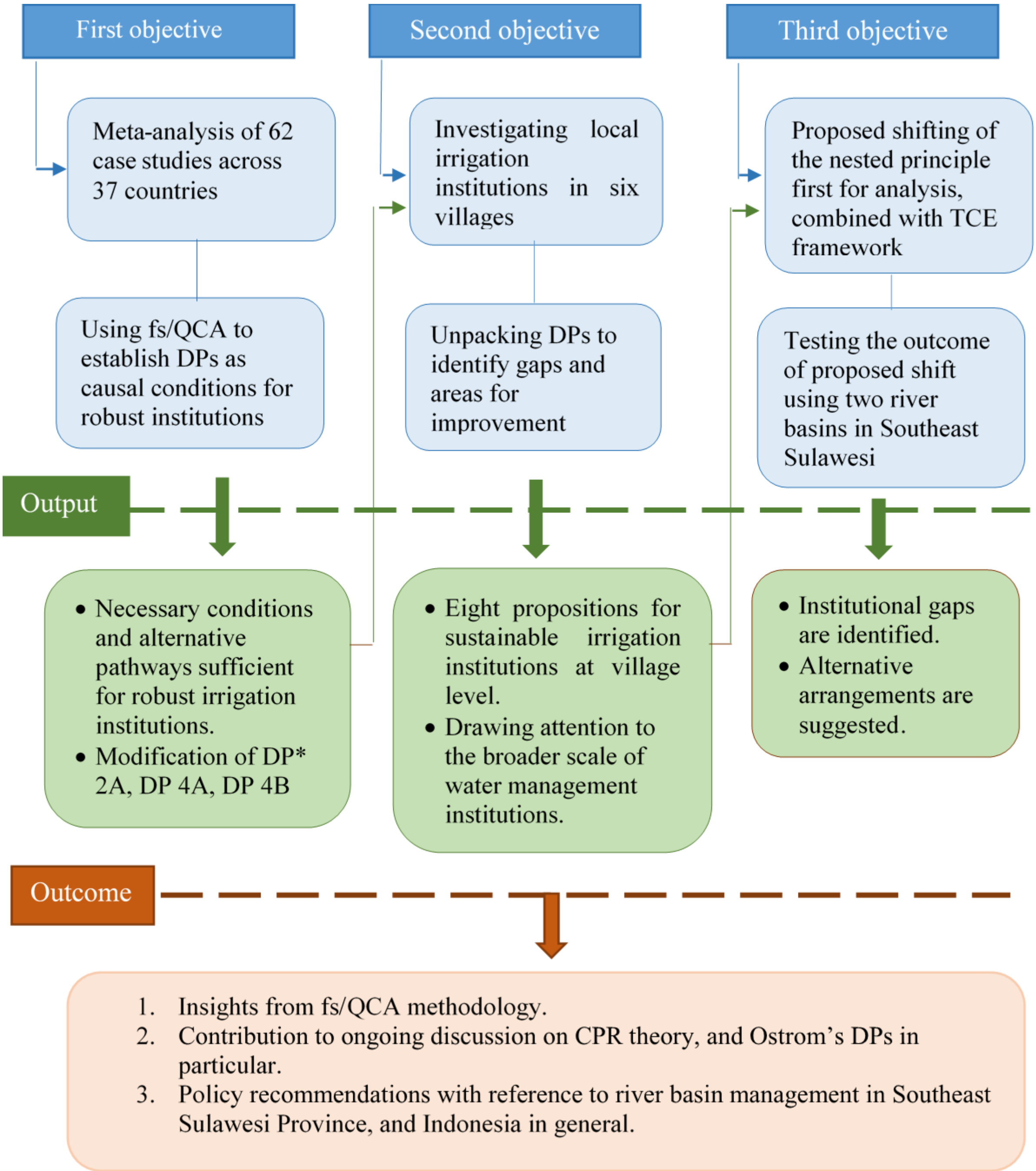

Figure 2. Research roadmap

1.7 Structure of the thesis

The thesis consists of five chapters: this introduction, three analytical chapters addressing the research objectives and the last chapter, which synthesizes the research findings and contains policy implications. The thesis adopts a manuscript style; thus, all the analytical chapters were designed as 'stand-alone' papers. Further, since **Chapters 3** and **4** are interlinked, the sections on data collection and methods contain some repetition. The outline of the remaining chapters is set out below.

Chapter 2 investigates the necessary and sufficient conditions for robust irrigation systems institutions through a meta-analysis of sixty-two irrigation system case studies drawn from thirty-seven countries. The study finds four necessary conditions, and two minimum configurations of conditions to ensure irrigation system institutions that are robust.

Chapter 3 examines alternative institutional arrangements for sustainable irrigation systems based on a case study of six irrigation systems in Indonesia's Southeast Sulawesi Province. The study uses a modification of Ostrom's DPs in Chapter 2. The study found that for self-governing irrigation systems to work, there is a need for them to be backed up by institutions at higher levels of management, which leads to the study in **Chapter 4**.

Developing the implications of **Chapter 3**, **Chapter 4** moves forward to analyze water management at a regional level and applies the revised order of Ostrom's DPs. The focus was on two river basins in Southeast Sulawesi Province; one is managed by central government, and the other by provincial governments. The framework for a social-ecological system for water governance is developed to analyze water governance in general. Here, the design principles were combined with the transaction costs economic approach to add rigor to the institutional analysis.

Chapter 5 provides a summary of the thesis, its contribution to existing scholarship, the limitations of this research and directions for future research. The contributions of the thesis were discussed in three sections outlined in this chapter. The first is the contribution to the fuzzy-set Qualitative Comparative Analysis calibration procedure, which is discussed in detail in **Chapter 2**. Second, it is demonstrated that the proposition to consider the nested principle first can provide a new perspective on how Ostrom's design principles can be used to analyze complex and large-scale common pool resources. The third contribution are the policy recommendations based on the exercise using the design principles in three different forms of analysis.

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Chapter 2: Robust irrigation system institutions: A global comparison

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.

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:
    i. Presence of clearly defined boundaries;
    ii. User involvement in monitoring and enforcement;
    iii. Comprehensive resource condition monitoring,
    iv. Minimum rights for users to organize.

2.1 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.

2.2 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.

2.3 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).

2.3.1 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.

2.3.2 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.

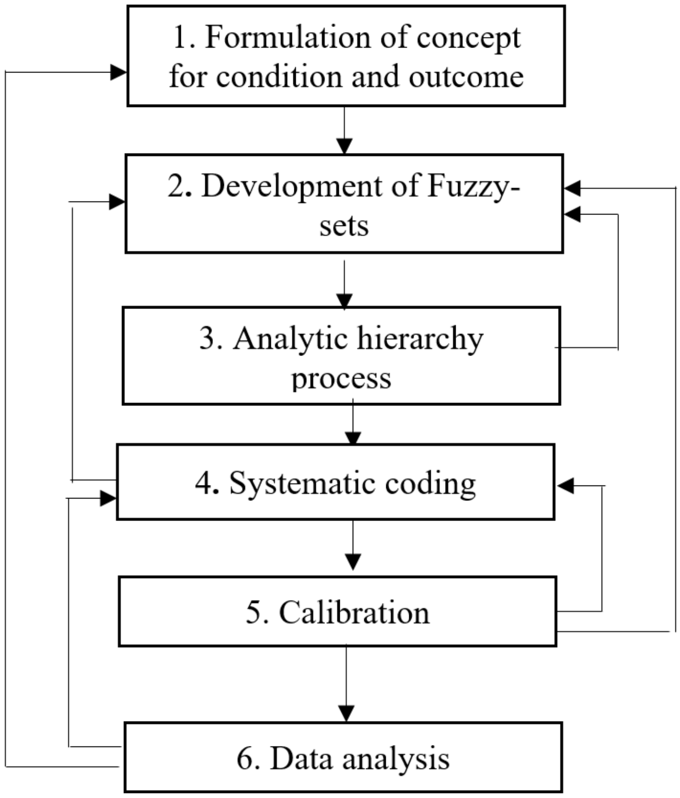


Figure 3. Scoring, coding and calibration procedure.

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.

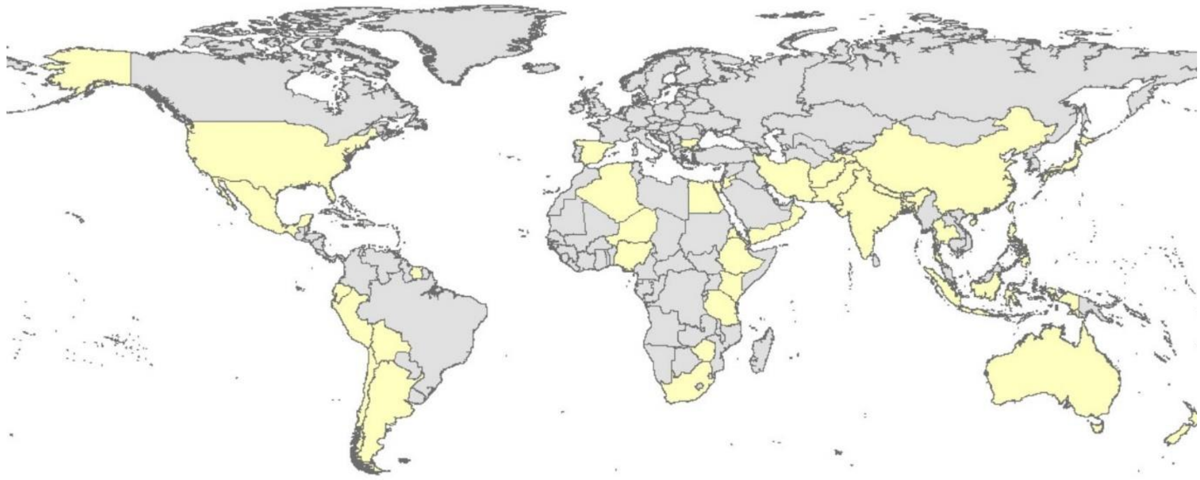
Table 2. Modifications to Ostrom's DPs for irrigation system case calibration

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.

2.3.3 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 4. 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).

2.3.4 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

2.3.5 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).

2.3.6 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.

2.3.7 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.

2.3.8 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.

2.3.9 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:

$$\text{BOUND*LOCCON*BENFCOST*COLLGOV*USERMON*SYSTMON*GRADSAN*CONFRES*RIGHT*NESTENT} \rightarrow \text{ROBUST} \quad (1)$$

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.

2.4 Results

2.4.1 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 6a. BOUND

	~BOUND	BOUND
ROBUST	2	41
~ROBUST	19	0

Table 6b. USERMON

	~USERMON	USERMON
ROBUST	0	43
~ROBUST	13	6

Table 6c. SYSTMON

	~SYSTMON	SYSTMON
ROBUST	0	43
~ROBUST	17	2

Table 6d. RIGHT

	~RIGHT	RIGHT
ROBUST	0	43
~ROBUST	10	9

2.4.2 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 5. 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).

2.4.3 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.

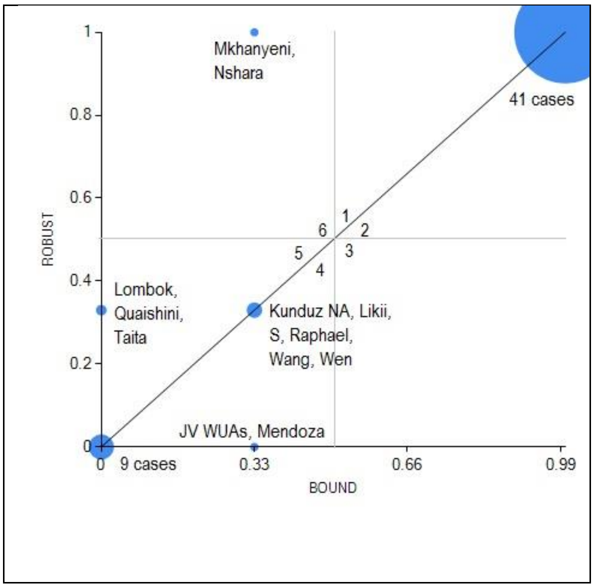


Figure 6. Enhanced XY plot of BOUND condition

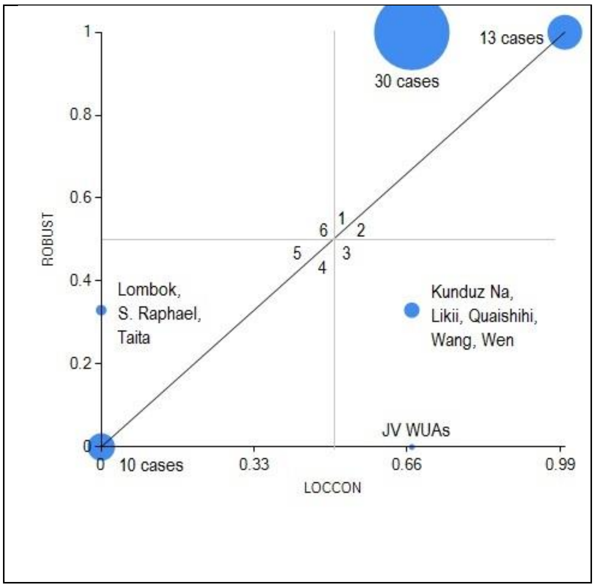


Figure 7. Enhanced XY Plot of LOCCON condition

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 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

[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.

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.

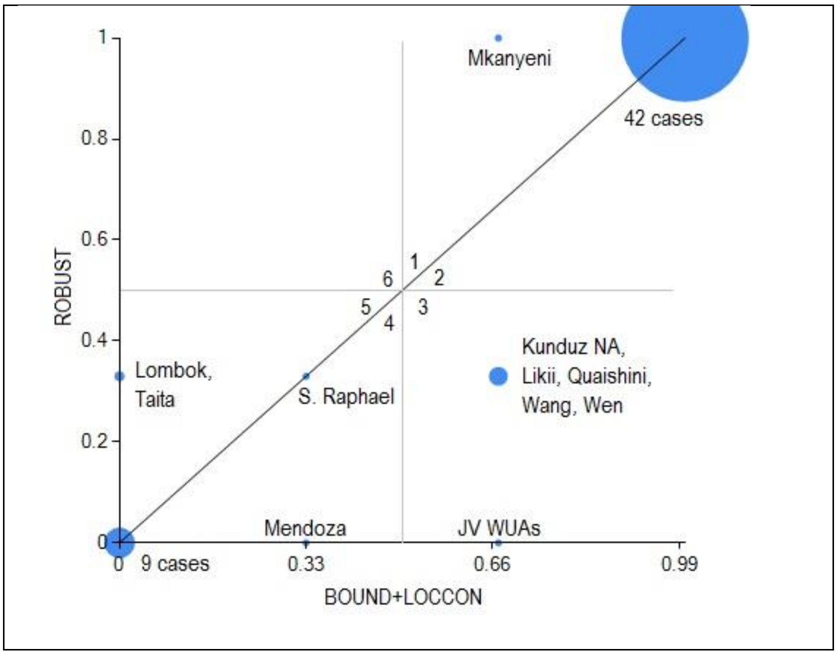


Figure 8. Enhanced XY plot of BOUND+LOCCON conditions

2.4.4 Sensitivity analysis

One way to test the robustness of fs/QCA 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.

2.5 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.

2.5.1 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 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 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.

2.5.2 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 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

[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.

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.

2.5.3 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.

2.5.4 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.

2.6 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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Chapter 3: Sustainable irrigation in Indonesia: a case study of Southeast Sulawesi Province

Abstract

This study employs Ostrom's Design Principles to examine the robustness of institutional arrangements employed by water user associations to manage access to water resources in Southeast Sulawesi Province, Indonesia. The outcome is a set of eight propositions which, if implemented, can be predicted to significantly improve water use in Indonesia. Emphasis is placed on the development of institutional arrangements that encourage and empower local action within an agreed system-wide framework so that communities can prosper as pressures and demands for water access increase—a requirement generally applicable to situations found in many other countries.

Keywords: sustainable irrigation, hierarchical arrangements, design principles

Highlights

- Indonesia like many countries faces increased water competition
- As a solution for irrigation, the country is exploring institutional change
- We employ Ostrom's design principles to identify institutional opportunities
- A return to cooperative arrangements is recommended via set propositions
- Locally-defined solutions are more likely to be sustainable in the face of change

3.1 Introduction

There are many examples of hydraulic civilizations that bear testimony to the benefits of collective water governance (Hassan, 2003). These civilizations can be described as resilient where they have enjoyed uninterrupted access to water for human consumption and for agriculture because of the robustness of the institutional design and social coordination mechanisms used (e.g. Brohier, 2016). Resilience in these systems was achieved, in part, because of the robustness of collective governance arrangements that over centuries have been able to evolve with changing demands, conditions and technology. The pace of change now, however, is much more rapid. As a result, new approaches and new systems are needed. The objective of this paper is to outline a series of propositions aimed at dealing with such rapid change needs, based on decision-making under uncertainty, using Indonesian data.

Irrigated agriculture in Indonesia started with small-scale, simple hydraulic systems around ancient Java in the 5th Century (Van Setten Van der Meer, 1979). It is believed that the irrigation system in ancient Java was similar to *subak* systems in Bali, where both employed cooperative irrigation arrangements based on relatively high levels of system organization and careful monitoring of effective performance (Van Setten Van der Meer, 1979). However, by the 15th Century colonial influences stemming from Netherland East Indies intervention on agricultural matters led to changes in the Javanese traditional arrangements, and by the 1930s differences of up to 50% were being recorded between Javanese and Balinese yields per hectare (Booth, 1977). This outcome is similar to what Bromley (1992) exemplifies as deterioration of local institutions following the emergence of colonial systems. Once Indonesia gained independence in 1945, irrigation development policies shifted to achieve government policy public objectives focused on increased production of irrigated rice. The achievement of self-sufficiency in rice production in 1984 was largely attributed to irrigated agriculture under modern centralized governance arrangements, but with increased tension between local farming systems and state or national institutions. Unlike their older cooperative governance counterparts, modern irrigation systems in Indonesia are at increased risk of failure in the face of rapidly altering demand and supply conditions. This is, in part, due to irrigation authority focus on infrastructure and maintenance issues, rather than management institutions, as a solution to existing problems. Thus, the resilience of Indonesia's modern irrigation communities will be being tested by increased local demand, changes to historic supply conditions, decreased local contributions to operating costs and maintenance, poor system performance, and increasing complexity as more users enter and compete for access to a previously abundant resource (Bruns, 2004; Sumaryanto, 2012).

In the last 30 years, successive regulatory changes have been made in an attempt to address this poor performance, with little success. Centralized approaches to modern irrigation management appear to be weakening local capacity to engage in collective management processes that previously enabled rapid resolution of local irrigation problems, and timely investment in improvements (Bruns, 2004; Pasandaran, 2004). Moreover, poor performance is viewed as a a consequence of deferred maintenance, justifying further construction of physical infrastructure (Bruns 2004; Suhardiman and Molinga 2012) over investments in institutional change. This may be because earlier attempts to transfer responsibility for system management back to local water user associations (WUAs) under the 1987 *Irrigation Operation and Maintenance Policy* (IOMP) (Oad, 2001) failed where local farmers no longer viewed labour contributions to maintenance necessary, and significant impacts on agricultural performance did not emerge (Vermillion et al 2002).

As a result, modern approaches to irrigation governance appear to be reaching their limits in Indonesia where institutional capacity for effective and efficient water reallocation is eroding and, from a government perspective, becoming increasingly expensive.

Consequently, the Indonesian government is searching for new water governance arrangements that can be expected to play a key role in resolving an increasing array of poor performance issues (Direktorat Irigasi & Rawa, 2011; Pasandaran, 2004). With these goals in mind, this paper searches for a set of institutional arrangements that will incentivize collective action at the local level and result in the emergence of institutions capable of: i) dealing effectively with future water supply uncertainty; ii) efficiently reallocating scarce water resources among competing demands; and iii) thereby increasing the potential for resilience in Southeast Sulawesi irrigation systems, with lessons for other areas. To achieve this aim, we first examine previous studies of collective institutional reform with respect to the improvement of irrigation management systems in Indonesia and elsewhere to identify relevant research questions. We then employ a case study of modern irrigation systems in Southeast Sulawesi Province to collect and analyze data on current irrigation governance arrangements and potential institutional changes. Finally, we discuss the implications of our analysis for Southeast Sulawesi—with a view to further application in other relevant regions.

3.2 Literature review

Small-scale irrigation systems can provide effective examples of long-lasting, self-governance institutions (Janssen and Anderies, 2013). Shepsle (1989) defines long-lasting institutions as robust where operational rules are devised and modified over an extended period such that governance institutions persist and cope under duress to produce efficient, socially-acceptable outcomes (Young, 2014). Often they are characterized by a rigid set of administrative structures and arrangements that enable rapid response to changing conditions (Young, 2019). A large body of literature documents the factors critical to positive performing governance institutions, where the choices for resolving dilemmas no longer focus on binary options, i.e. the state or the market particularly where issues of equity and sustainability are involved (Agrawal, 2001). To accommodate equity or sustainability issues, collective action governance has often been recommended. With regard to collective action, Wade (1989), Ostrom (1990) and Baland and Platteau (1996) suggest such choices are most prominent when and where property rights are well-defined, legally protected, and shared equally. Ostrom (1990) examined both public and private property right institutions and, ultimately, came to the conclusion that the public versus private debate was missing a third alternative—namely the development of self-governing institutions. Unlike Olson's (1965) pessimistic view on the possibility that individuals can contribute voluntarily to achieve common interest, Ostrom (1990) found that individuals have the capacity to devise specific management and maintenance rules with either no or limited intervention by external parties. Building upon this insight Ostrom provided eight general principles for the development of sustainable governance systems (Ostrom, 2008). According to her, these design principles (DPs) provided a basis for the development of successful self-governing institutions and, more importantly, identifying the changes need to repair systems which, for one reason or another, have become dysfunctional (Ostrom, 1990). However, Steins and Edwards (1999) showed in their case study that, while the design principles may all be present, if cooperation is hampered by contextual factors, dysfunctional outcomes may persist. Similar findings are reported from case studies in China by Yu et al. (2016) and Kenya by Dell'Angelo et al. (2016) where, despite the presence of Ostrom's DPs, significant access inequality and a total dwindling of water resources ensued. Based on their observations, Yu et al concluded that Ostrom's DPs were insufficient to assess successful irrigation institutions. Further, Del Angelo doubted the capacity of the DPs to cope with rapid change in socioecological contexts.

We concur with Steins and Edwards' (1999) view that contextual factors matter when using Ostrom's DPs as an analytical framework, as Ostrom herself warned against treating the DPs as a panacea (Ostrom, 2007, 2008; Ostrom and Cox, 2010). Instead, we believe it more appropriate to use the DPs as a diagnostic approach for analyzing and identifying practical institutional change (Ostrom, 2008; Ostrom and Cox, 2010), while taking into account the local context or characteristics under observation within the system-wide set of arrangements. Thus, when examining existing local institutions—or the need for change—it is more meaningful to turn the DPs into questions, as Ostrom (2008) suggested, so that current (nested) institutional arrangements can be tested and improved to better manage future common goals in the face of dynamic change (Ostrom and Cox, 2010).

Therefore, in this paper we search for the DP conditions and institutional arrangements that, if implemented, would improve water use, enable more efficient management of changes to supply and demand conditions in Southeast Sulawesi, and improve community resilience. We define resilience as the capacity for an irrigation community to react, adapt and avoid resource deterioration that may arise from internal or external disturbances (Aligica and Tarko, 2014). As a result, we are interested in: i) whether or not there is scope for institutional change at the local level relevant which could inform Southeast Sulawesi irrigation management system reform; and ii) if so, what institutional reforms should be considered? Previous studies elsewhere in Indonesia have evaluated effective policy reform to improve irrigation management, institutional performance (e.g. Bruns et al., 2005; Oad, 2001; Suhardiman, 2013; Suhardiman and Mollinga, 2012), participatory organization (Ricks, 2016), and the general performance of farmer-managed irrigation systems (Pasaribu and Routray, 2005; Sutawan, 1987). Very few, however, have studied or suggested practical institutional arrangements at the local level, and their potential to deal with the challenges now facing water users in Southeast Sulawesi. Therefore, the contribution of this study is a local-based analysis aimed at informing a wider set of institutional design requirements. The case study highlights how local institutions might grow in their capacity to manage current supply/demand constraints and, at the same time, provide opportunities for other economic sectors to grow.

3.3 Material and Methods

3.3.1 Case study area

In order to explore the case for change, we decided to focus on the Southeast Sulawesi Province in eastern Indonesia (Figure 1). As it receives around 2,000 mm of mean annual rainfall, the Province of Southeast Sulawesi is considered a water abundant province (BWS Sulawesi IV, 2012). Prior to the 1980s, this abundant rainfall meant that irrigated agriculture was not common among the indigenous population. Shifting cultivation was common practice and most agriculture crops were rain-fed. Consequently, as is the case in many other parts of Indonesia, the province has not had a deep historical or cultural experience with water management. Small scale irrigation systems were first introduced by migrant farmers from Java, Bali and Lombok who settled in the province in the early 1970s. The first major irrigation projects took place in 1988 with the construction of *Bendung Wawotobi* (Wawotobi reservoir) on the *Konaweha* River. Initially around 18,000 hectares of rice paddy farming was established. This was followed by construction of the *Bendung Ameroro* reservoir and a number of other smaller reservoirs. Unlike the larger *Wawotobi-Ameroro* irrigation districts (ID), irrigation farming in other districts relies upon the extraction of water from smaller rivers or streams with highly variable flows during wet and dry seasons; i.e. not all the IDs have reservoirs to regulate water.

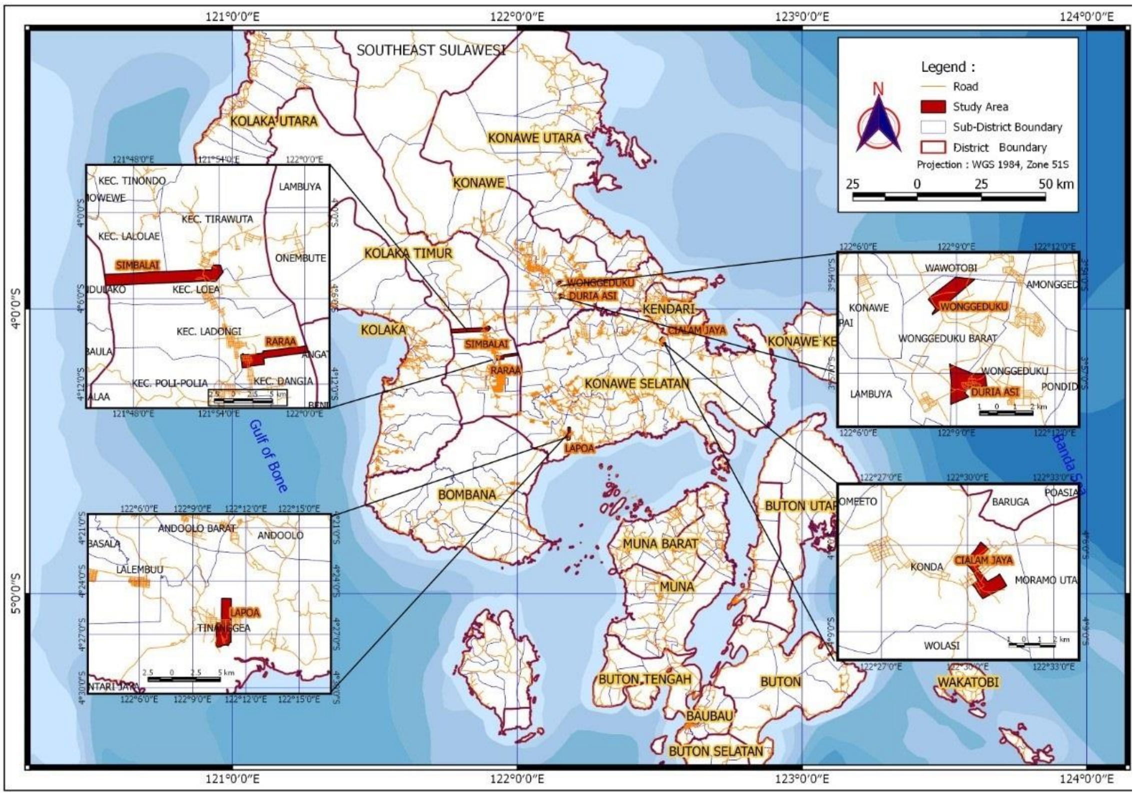

Figure 9. Map of study area in Southeast Sulawesi Province and irrigation villages

There are signs that the irrigation management systems being used in Southeast Sulawesi are approaching failure. Decreasing irrigation water availability, for example, has been noted in *DAS Konaweha* (Konaweha watershed) as a result of upstream land-use changes including deforestation to enable construction of new upstream rice paddies, establishment of palm oil or pepper cropping, and increased sand or other mining activity (Baco, 2012; Marwah, 2014). Baco (2012) forecasts that upstream land-use change will decrease total water availability up to 39% by 2031-2035 (as compared to the period 2011-2015), with further reductions to total supply of up to 60% by 2046-2050. During this same period, it is expected that water demand will increase from 29m^3/second in 2031-2035 to 33m^3/second in 2045-2050 (Baco, 2012). At present, demand is 24m^3/second (2011-2015), which represents an emergent demand supply gap that is nearly as large as current use (Figure 2). Clearly, this is infeasible.

Development of a suite or mix of institutional arrangements that are capable of managing the resultant tensions is becoming increasingly urgent. At some stage in the next ten years, demand can be expected to regularly exceed supply. It is important to note that *DAS Konaweha* is the biggest and most strategic river in Southeast Sulawesi as it supplies water for various purposes across four districts. Further, similar supply reductions/demand increases are also expected for other rivers and watersheds in the province.

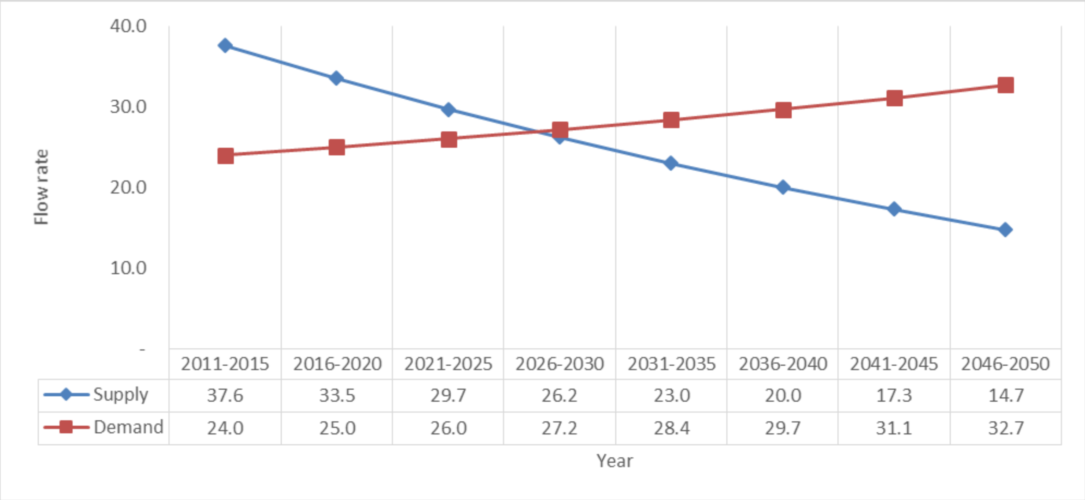

Figure 10. Forecast of Water supply and demand in *DAS Konaweha* Watershed as a result of continuous land-use change (Baco, 2012)

In such a situation, typical policy responses search for ways to augment supply in an attempt to postpone institutional reform (Young, 2019). Rather than taking this approach, and in a stark break from previous governance choices discussed above, the Indonesian government is applying a concurrent strategy involving a search for new water supplies *and* institutional reform. With regard to supply enhancement, two multi-purpose dams are being proposed with the capacity to provide 23,644 new hectares of paddy fields, 850l/s of fresh drinking water to urban users, and 22.5MW of electricity in total. On the back of these expected gains, other small reservoir projects in the province have been planned and are awaiting implementation.

At the same time, the Indonesian government is looking closely at how best to restructure, form and develop new organizations and institutions capable of managing this constellation of challenges. In order to assist with this process, we have used Ostrom's DPs as a framework of questions to guide the collection of qualitative data from key stakeholders in the province using interviews, focus group discussions and workshops. In this paper, we focus on the nature of required water policy reforms at the water user association level and, while we draw attention to the need for reforms at the district, provincial and national level, we leave full consideration of this dimension to another paper. We do this partly because of the methodology used and partly because we found that Ostrom's design principles are written in a manner that avoids full consideration of this important dimension of many governance issues associated with water.

3.3.2 Data collection

The study was designed to explore different perspectives of irrigation institution at local levels from farmers and irrigation officials, and to contextualize where these farmers and irrigation officials perform their activities. Therefore, we used a number qualitative approaches to collect field data that represented a broader perspective on irrigation institutions from multiple sites for comparison, which we could also use as a method of data triangulation (Yin, 2011).

Interviews, a stakeholder workshop, and focus group discussions were carried out between August and October 2017. Except for farmers' groups, all participants were chosen purposefully considering their roles and activities directly related to water allocation or work in the irrigation sector at different levels. Farmer participants were invited through their village heads or water user association. In the beginning of each data collection activity participants were provided consent forms to record their agreement to participate, noting that they could withdraw at any point during the data collection process without penalty.

We conducted interviews with 15 officials at different management levels including staff from agriculture departments, heads of villages, and heads of WUA Unions. Topics discussed included water resource and irrigation management issues in respective areas, what methods (if any) are used to allocate water to different uses, and what problems or conflict (if any) resulted from the use of water resources. We also took the opportunity to seek guidance on the most appropriate villages in which to hold focus group discussions (FGDs).

The stakeholder workshop was facilitated by the Department of Research and Development in *Kendari*, the capital of the province. The workshop involved 18 invited stakeholders from government institutions including state water companies, River Basin Organisations, the Forestry Department, the Watershed Management Institute, the Environment Department, and the Department of Regional Planning. The aim of the workshop was to collect a further layer of supplementary qualitative data in support of the institutional analysis and, in particular, to allow fuller consideration of the views of those responsible for provincial level management.

FGDs were subsequently carried out in three *kabupaten* (districts): *Konawe*, *Konawe Selatan* and *Kolaka Timur*. Two villages were chosen to represent each district in an effort to ensure representation in the FGDs of diverse water resource conditions and institutional arrangements. Five to eight farmers, including heads of district *Perkumpulan Petani Pemakai Air* (P3A or farmers' groups/WUAs) participated in each FGD—typically conducted in a local farmer's house. During the FGDs, farmers were asked to reflect on: the water management arrangements in their WUAs; how water was allocated among farmers through the tertiary canal infrastructure; what rights and responsibilities existed in the irrigation system; the risk (if any) of water shortages; problems and future uncertainties (if any) within the system; and existing mechanisms (if any) to resolve water allocation conflict. Follow-up interviews were later conducted with some FGD participants to clarify issues that were identified as missing from the dataset and/or not clear to the research team following reflection on the nature of the information collected.

3.3.3 Data coding and analysis

As discussed above, Ostrom's design principles provided the question framework for this study. Consistent with prior research, we utilized a modified version of Ostrom's DPs (Ostrom, 2010) created by Ma'mun et al. (under revision). This modified list brings a sharper irrigation focus to Ostrom's original list of principles for the management of water resources, and focuses on conditions for the realization of robust governance systems. These modified DPs were derived from a meta-analysis of 62 case studies from 37 countries. As a basis to organize our data, Table 1 provides the list of Ostrom's DPs modified by Cox et al (2010), except for DP2A, DP4A and DP4B where we used the definition from Ma'mun et al (under revision) to fit the water/irrigation case.

Table 10. Ostrom's design principles

	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 condition	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 users	Monitors are accountable to the users with enforcement capacity for ensuring compliance to the appropriation and use rules.
4b.	Monitoring of resources	System-wide monitoring and reporting exists and is reported to users.
5.	Graduated sanction	Appropriators who violate operational rules face sanctions, preferably graduated.
6.	Conflict resolution mechanism	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 enterprises.

Coding of the data follows Ostrom's (2008) suggestion to think of the design principles as a starting point for identifying practical implications from the design principles, i.e. identifying appropriate arrangements to improve water management at a local level. We then used Yin's (2011) procedure which i) *compiled the field notes* into general themes, ii) *disassembled the data* using Ostrom's DPs as overarching concepts, after which we iii) *reassembled the data* by unpacking the DPs into elements relevant to water characteristics and whose presence was easier to observe and analyze (Simon, 1978), then we iv) *interpreted the reassembled data*, and finally v) *drew conclusions* from the entire study. We used the initial interpretation stage to revisit and refine the reassembled data, and arrived at the DPs' elements displayed in Table 2.

Table 11. List of design principle elements for coding the data.

Design principles	Description and support from the literature
1. Clearly defined boundaries Legitimate user Limit of water withdrawal Rules for new entrants Security of tenure	The elements need to consider whether the legitimate user are easily identified, how much water can they take from which point, and whether their use rights is secured and protected (Howe et al., 1986; Matthews, 2004; OECD, 2015)
2A. System congruence with local condition Flexibility Reliability of supply Transferability Expectation for future irrigation	The congruence with local and system wide condition need to have flexibility in a defined structure so that the outcome can be predicted and so that that the users can adapt to various changes (Howe et al., 1986; Young, 2019)
2B. Appropriation and provision rules Contribution to O&M Cost recovery	Unlike traditional irrigation systems which simple in nature and easier to maintain, modern irrigation systems are capital intensive, thus making the cost recovery become one of the major issues (Sampath, 1992; Ward, 2010).
3. Collective choice arrangement Farmer’s participation Accountability	Involving most farmers in collective governance is not always effective or feasible. Thus involving individual who can act as trusted representative should be acknowledge (Meinzen-Dick et al., 2002).
4A. Monitoring of user Accountability Enforcement capacity	Apart of the accountability of the monitors, effective monitoring should have enforcement capacity to ensure compliance to the operational rules (Ma’mun et al 2019; OECD 2015).
4B. System wide monitoring Access to information Transparency	Successful management requires constant monitoring of resource system and that the information available in timely manner to enable community to adjust and adapt to various water resource condition (Folke et al., 2005).
5. Graduated sanction Informal sanction Formal sanction	Types of graduation sanction may be informal or formal, and has been discussed in the literature (Ostrom 1990; Cox et al. 2010 and many others).
6. Conflict resolution mechanism (CRM) Local CRM Formal CRM	The elements of the DP were discussed in clearly in irrigation case studies in Ostrom (1990).
7. Minimum recognition of right to organize Autonomy Acceptability\	The important of authority system of self-governing institution and its acceptability by local community and external government had been discussed by Bromley (1992) and Dinar et al. (1997).

8. Nested enterprise Vertical and horizontal coordination	Since irrigation system is part of complex water/river system, horizontal and vertical coordination become important to ensure that the community can realize their socioeconomic objectives within a defined system-wide framework (Knieper and Pahl-Wostl, 2016).

Ultimately, the coding and analysis resulted in a better understanding of the local context and characteristics for the case study areas, and a final set of coded DPs within those local contexts. This enables us to follow Ostrom's (2008) suggestion that the DPs be used to answer questions of how to improve the broader set of irrigation management institutions in Southeast Sulawesi.

3.4 Results

3.4.1 Village context

In the main, results provide further evidence of poor institutional performance in Southeast Sulawesi irrigation districts. We begin with some general village context. All village farms are served by public irrigation systems with reservoirs to regulate water, except for *Cialam Jaya*, which relies on water extraction directly from their stream. Two villages (*Duria Asih* and *Wonggeduku* in the *Konawe* district) receive water from the *Wawotobi* reservoir which helps avoid seasonal water shortages. Water supply in other villages are more variable. Atypically, *Cialam Jaya* also has a domestic water supply system managed by a village-owned company. Most village households have an average plot size of one hectare that is used predominantly to grow two rice crops two times a year. Over the last 10 to 15 years, all of the villages have experienced a trend of decreasing water availability and, also, a range of water quality issues.

Table 3 provides a more detailed overview of the village by village issues identified during the FGDs. Significantly, participants from the *Konawe* and *Kolaka Timur* districts identified upstream expansion of palm oil plantations and illegal logging in the *DAS Konaweha* watershed as prime causes of reduced flows and a decline in water quality. Farmers and irrigation district officials also reported water quality issues caused by C-type (sand) mining within the riverbed which has increased sedimentation in both the river and irrigation supply canals. Importantly, the expansion of palm oil plantations and mining operations have occurred with district and central government approval following the receipt of positive technical recommendations from the *Balai Wilayah Sungai Sulawesi IV* (BWS) and permits enabling these developments from both district governments and the central Department of Energy and Mineral Resources. FGD participants, however, informed us that while these permits do not allow downstream impacts, a general lack of enforcement (despite monitoring) means that any negative externalities go unpunished.

Local problems also exist. Farmers in *Duria Asih* voiced their concern on water quality during the FGD. It is common for some people to use poison when fishing in the canals during low flows, and for pesticides to be overused by farmers leading to water quality issues. This problem was echoed by the irrigation official in *Wawotobi* ID. As a result, the state-owned water company located downstream on the *Konaweha* River reported that it had to spend significant amounts of money purifying water for city and domestic use.

Table 12. Summary of selected village characteristics and water related issues

	Konawe District		South Koanwe District		East Kolaka District	
	Wonggeduku (West Wonggeduku Subdistrict)	Duri Asih (Wonggeduku Subdistrict)	Cialam Jaya (Konda Subdistrict)	Lapoa (Tinanggea Subdistrict)	Simbelai, Loya Subdistrict	Raraa, Ladongi Subdistrict
Population/HH	1256/242	1347/349	1726/426	1133/290	1811/NA	2333/NA
Irrigated area (ha)	± 250	± 175	± 245	± 122	± 171 + 50 ha (new)	± 320
Water source for agriculture	Konaweha River (Wawotobi ID)	Konaweha River (Wawotobi ID)	Springs, wetland and groundwater	Lapoa River (Lapoa ID) + groundwater	Loya ID from Loya and Nango-Nango Rivers	Ladongi River : Ladongi ID + Gunung Jaya ID groundwater
Water management type	Farmers' groups	WUA & farmers' group	Farmers' groups	WUA & farmers' group	WUA & farmers' group	WUA & farmers' group
Participation in operation and maintenance [O&M] (irrigation service fee [ISF] or in-kind contribution)	IDR 100/100m^2/season (zero compliance), Labor contribution	IDR 17,500/ha/season, grain contribution of 20kg/ha/season for Ulu-Ulu and canal cleaning, Labor contribution	Labor contribution	IDR 25,000/ha/season (zero compliance) Labor contribution	±4 cans of grain/ha/ season for Ulu-Ulu Labor contribution	2 cans of grain (about) 20kg/ha/season for Ulu-Ulu, Labor contribution
Risk of water shortage	Low (rarely experience water shortage in the last 10 years)	Low (rarely experience water shortage in the last 10 years)	High risk of water shortage especially at the tail-end of an irrigation system	High risk of water shortage especially at the end tail of an irrigation system	High risk of water shortage especially at the tail-end of an irrigation system	High risk of water shortage especially at the tail-end of an irrigation system
Water allocation during shortage	Water rotation in the first two weeks of 2nd cropping season at secondary canals	Water rotation in the first two weeks of 2nd cropping season at secondary canals	Natural flow, where end of the system gets the highest risk of water shortage	Water rotation between paddy field area (right and left side of the canals)	Water rotation among farmer groups	Water rotation among farmer groups
Problems/water-affecting activities	Land use change: palm oil plantation, deforestation; water quality (type-C sand mining)	Land use change: palm oil plantation; deforestation, water quality (type-C sand mining; overuse of pesticide; fish poisoning in the canals	Deforestation; long drought	Land use change; new paddy fields in upper river; discharge of materials from nickel mining; long drought	Land use change: new paddy fields within the irrigation system; pepper tree farming	Deforestation; pepper tree farming

HH = households; NA = not available

In the *Konawe Selatan* district, especially the *Tinanggea* subdistrict, nickel mining has resulted in adverse impacts on water quality. In FGDs, farmers reported that mining is causing siltation in the *Lapoa* River and reducing flows through irrigation canals. The worst reported siltation case was in the *Roraya* village irrigation system where four hectares of rice fields had been destroyed which, for the farmers involved, has meant that they have lost access to their investment in the village irrigation system and also their asset and income. Maga (2018) has estimated that this uncompensated impact costs those involved AUD$15,000. In fairness, local irrigation staff have sought justice for the affected farmers by reporting the losses to provincial government authorities but, at the time of writing, there has been no redress. Worsening the extent of the problem, development of the nickel mine also made it possible for around 100 hectares of new rice fields (*sawah*) to be established above the small *Lapoa* reservoir near *Asingi* village in a manner that is expected to reduce the quantity of water available downstream. At the other end of the river system, and as a result of unapproved upstream development, the low-lying *Raraa* village both receives less water during the dry season and, also, is now more prone to flooding during rainy seasons. FGD participants from *Raraa* reported that, in the rainy season, around 70 hectares of village farmland is now regularly water-logged and that, as a result, local villagers and irrigation officials have been trying for two decades to obtain permission to build a drainage canal through the *Rawa Aopa* National Park to address this issue. Their power, however, is far less than that of the National Park Management Authority and affected farmers have become deeply dissatisfied because they have to pay the same taxes as any other farmer even though their land is much less productive. Overall, these general FGD observations support a view that the value of the existing property rights system is perceived as worthless and, as a result, the level of farmer dissatisfaction is high and farmer participation in system maintenance is low. Against this background we can now turn to a consideration of Ostrom's modified DPs in search of a suggested solution.

3.4.2 Using modified DPs to evaluate institutional arrangements

Several different institutional arrangements were found in the study areas (Table 4). For each of the ten modified DPs, we expand those arrangements to identify areas of institutional change that might improve management and performance—included as propositions.

Table 13. Summary of evaluation based on themes discussed in the FGDs.

Design Principles	Evaluation of existing arrangements
1. Clearly defined boundaries	
Legitimate user	Member of WUA or paddy farmer in the irrigation service area
Limit of water withdrawal	Unclear, based on land sufficiency (for paddy)
Rules for new entrants	Not clear
Security of tenure	Weak
2A. System congruence with local conditions	
Flexibility	Water rotation during water shortage period
Reliability of supply	Other than WUAs in *Wawotobi* ID, high uncertainty of water supply in the dry season especially for the tail-end of irrigation systems
Transferability	Not allowed
Expectation for future irrigation	Only WUA in *Lapoa* has clear contingency plan for future water conditions
2B. Appropriation and provision rules	
Contribution to O&M	In-kind contribution for water master payment and canal cleaning
Cost recovery	No cost recovery. Only the *Duria Asih* WUA has implemented an irrigation service fee (ISF) for operational costs and minor maintenance
3. Collective choice arrangements	
Farmer's participation	Not all farmers participate in rule-making processes
Accountability	Respected/strong leadership in *Lapoa*, *Duria Asih* and *Simbelai*
4A. Monitoring of users	
Accountability	Self-monitoring exists in all WUAs
Enforcement capacity	Weak enforcement capacity, especially for those outside the system(s)
4B. System wide monitoring	
Access to information	WUAs have easy access to information on water availability from the water master(s)
Transparency	Every WUA has agreed planting schedules in each ID, known to its members
5. Graduated sanctions	
Informal sanction	Informal sanctions applied for rule infringements in all villages
Formal sanction	Only *Simbelai* has formal sanctions
6. Conflict resolution mechanisms (CRM)	
Local CRM	Local informal conflict resolution exists in all villages
Formal CRM	Formal mechanisms are not effective and easy to access when conflict arises with outside users
7. Minimum recognition of rights to organize	
Autonomy	Farmers are encouraged to form WUA to manage their own tertiary canals
Acceptability	WUA in *Cialam Jaya* is less acceptable of rights to organize. Farmers organize themselves in groups according to source of natural flow for village irrigation
8. Nested enterprise (not applied to *Cialam Jaya*)	
Vertical and horizontal coordination	Strong vertical and horizontal coordination between WUA and irrigation officer under Department of Public Works Lack of coordination with other related departments/sectors Strong inter-village linkage in the *Lapoa* ID

1) DP1: Clearly defined boundaries

This principle relates to limits on the total amount of water that may be taken by new users and options for the definition of this limit. Irrigation system boundaries in Southeast Sulawesi typically conform with initial irrigation system development areas. As development expanded, new farming (paddy field) areas were opened or extended, and legitimate water users were allowed to access water only within the irrigation service area. However, farmers do not enjoy individual physical water withdrawal unit rights; their share of total water resources is usually set at district level. Thus, the only limit on water withdrawal is related to the land area owned by farmers and the rules associated with access.

For example, the *Wawotobi* ID has (for now) a reliable annual supply, while the *Lapoa* and *Simbelai* village WUAs need to implement strict farm-rotations of irrigation water during dry periods. Water shortages during dry seasons are not, however, shared equally across farm districts. As a result, farmers in the *Raraa* village appear to be losing out as a result of upstream development. Initially, *Raraa* was part of the *Ladongi* ID and its' 2,722 hectare area. However, due to a tail-end location and, as all *Raraa* farms could be supplied by *Ladongi* ID with enough water for a second rice-crop, it was decided to allow them to make use of groundwater, pump water from the drainage system, or attempt to get access from the neighbouring village (*Gunung Jaya*) on the understanding that they would be exempted from some WUA obligations. While pragmatic in its outcome, this action illustrates the importance of defining boundaries to access in a rigorous manner and, if system function is to be maintained, then establishing mechanisms that prevent increased access without compensation.

Illustrative of the extent of this challenge, in the *Lapoa* and *Loya* IDs, for instance, FGDs participants stated that they thought they would eventually need to share their water with the new rice paddy user. They also highlighted differences between 'legitimate' paddy field new users and 'illegitimate' pepper tree farmers who steal water from primary and secondary canals in the *Loya* and *Ladongi* IDs. Some FGD participants recognized that pepper farmers received a livelihood from their trees, and needed water to keep these trees alive to protect long-term investments—however, none were able to identify a solution to the problem. We suggest a first proposition solution as follows:

> Proposition 1: *System robustness can be improved by formally defining a limit on water withdrawal for individual farmers, either by area or volume, and clear criteria for priority allocations if/when scarcity occurs.*

2) DP2A: System congruence with local conditions

Sustainable use requires appropriation and provision rules that are compatible with local social-economic and environmental conditions (Cox et al., 2010; Ostrom, 1990). Thus, the system's water allocation arrangements must be able to adapt with new or altered conditions in a manner that simultaneously maintains consistency with biophysical realities, is judged to be fair, and promotes socio-economic progress (Young 2014). As a test, it should be possible for changes to be made to allocation arrangements in a manner that does not result in an increase in conflicts and/or a decline in compliance with operational rules. FGDs revealed that not all WUAs in Sulawesi met this design principle. For example, the *Cialam Jaya* system delivers natural flows to end-tail irrigation users but without the capacity to modify water allocations among users as flow conditions change. In particular, it is not uncommon for mutual consensus arrangements between users to occur in a manner that violates other users' capacity to access water.

During the second cropping season in *Cialam Jaya* when flows tend to be lower, there is no agreed set of rules for working out how to partition access between farmers who access water directly from the river and those who can access water only when it reaches the end of a canal. Failure to address this local congruence DP means that there is a large degree of water supply uncertainty with the consequence that farmers are unwilling to pay operational and maintenance costs. Thus, since its formation in the 1990s, the WUA has not been able to function properly. However, appropriation arrangements in *Lapoa, Simbelai* and *Raraa* villages are better that those of *Cialam Jaya*. During low flow periods farmers share the available water by rotation between blocks, quaternary, or tertiary canals. Even so, low flows coupled with water losses along the distribution channels make water supply to tail-end farmers insecure. Some of these farmers use groundwater to augment supply, which incurs additional costs of fuel in their agricultural (rice) production. Water abundance in the *Konaweha* River allows farmers in *Wonggeduku* and *Duria Asih* to enjoy more reliable supply compared to other areas. Any required water rotation takes place at main intakes along primary or secondary canals. However, without clearly defined withdrawal limits farmers at the top of the irrigation system have been taking water indiscriminately, causing tail-end farmers to wait to receive water. This increases the risk of crop failure due to water logging or shortages in the first and second cropping seasons respectively, as mentioned by irrigation staff in *Wawotobi* ID.

Importantly, there is a need to develop appropriate rotation or other mechanisms that enable enforcement of any modified ‘property rights’. If this could be achieved, there would be increased transparency and the creation of institutional conditions necessary to allow all users to better plan and adopt coping strategies for the management of supply scarcity. Maintenance of transparency and fairness in the process of water allocation might also help improve farmers’ willingness to contribute to the costs of operation and management. Our second proposition for Indonesian systems is therefore:

> <u>Proposition 2:</u> *All farmers in WUA-managed areas need to be registered and records need to be kept and updated by the WUA. Records may include total area, number of plots, location, and type of crops (in different seasons), and rules for water sharing during periods of supply scarcity.*

3) *DP2B: Proportional equivalence between benefits and costs*

This design principle requires that the cost of irrigation system operation and maintenance (O&M), whether cash or in-kind, is equivalent to the benefit that farmers receive—and will depend on how institutional arrangements in other DPs provide farmer incentives to recognize these benefits/costs. In Indonesia, in addition to labor contributions toward canal cleaning before planting, farmers commonly pay the *Ulu-Ulu* (water master) a unit of harvest each season (see Table 2). Within the IOMP framework in 1989, an irrigation service fee (ISF) was introduced to cover some of the cost of irrigation system maintenance. Typically, the size of this fee is agreed upon by WUA members and used to pay for administrative costs and minor maintenance works. Our FGDs, however, revealed that the *Duria Asih* is the only WUA that has managed to collect an ISF from its members on the understanding that any member who cannot pay the ISF is required to work on designated tasks arranged by the WUA. This enables the WUA to financially contribute to the WUA Union (GP3A, *Gabungan Perkumpulan Petani Pemakai Air*) at the secondary canal level.

Flexible ISF payment methods for irrigation O&M are worth considering in more detail. A reason for past sustainability in *subak* systems was a combination of service-provision and monetary obligations by members (Birkelbach, 1973; Geertz, 1964). The estimated total monetary and labor requirements for routine maintenance were carefully calculated, and members could purchase exemption for excess labor proportional to land owned. Yet levies for extraordinary activities were also imposed on an *ad hoc* basis (Birkelbach, 1973). In Southeast Sulawesi, beside in-kind payments to *Ulu*-Ulu, farmers' contribute mainly to canal cleaning before planting season as discussed, and minor repairs beyond 50 meters of tertiary canal sections. To support extended tertiary canal maintenance, governments provide public funding through the Department of Agriculture and/or the Ministry of Public Works under the *Program Percepatan Peningkatan Tata Guna Air Irigasi* (P3-TGAI). The program is intended to increase farmers' participation by providing funds directly to WUAs to rehabilitate and improve their irrigation system, but in general it is not expected to motivate increased farmer participation in system maintenance. Thus, WUA members need to agree on mechanisms that enable them to recover the cost maintaining the productive use of irrigation systems if/when government funding is no longer available. Therefore, our third proposition follows:

> Proposition 3: *Providing choices for ISF payments through service or monetary obligations, or a combination of both, may increase farmer contributions to irrigation O&M.*

4) DP3: Collective choice arrangements

Effective irrigation performance includes two major decision-making activities: i) setting the cropping schedule and ii) setting working rules within the WUAs. At present, public irrigation system cropping schedules are decided at the district level with inputs from the WUA (or farmers' group) and irrigation field staff. Not all farmers participate in the process, and may instead send a representative from their WUA or farmers' group. The process usually involves a report from the *Ulu-Ulu* that summarizes what farmland went into production (*lahan fungsional*) in the last season/year. After this initial progress has been received, however, the system outcomes may vary significantly. In the *Konawe* district a cropping plan for all sub-districts is decreed by the district head (*Bupati*) based on recommendations from the Irrigation Committee. By contrast, in *Konawe Selatan* and *Kolaka Timur* WUA or farmers' representatives attend a meeting organized by *Pengamat Pengairan* (Irrigation Overseer) to discuss the cropping season before it begins. Finally, in *Lapoa* WUAs and farmer groups from the four villages belonging to *Lapoa* ID make decisions on water rotations and which WUA in the ID receives priority water allocations—particularly during dry seasons. In most villages either young innovative farmers and/or senior respected leaders often play a role in bringing the irrigation community together and acting as mediator when conflicts arise.

In conclusion, with regard to the nature of collective choice arrangements in Southeast Sulawesi irrigation we suggest that these require no change.

5) DP4A: Monitoring of users

Monitoring is essential for evaluating the performance of any system. In the villages studied, farmers typically reported self-monitoring of use/users while going about their daily activities. Their motivation was to ensure they received their resource provision, while also checking resource conditions and water extraction activities by other farmers/users. Self-monitoring ensures user compliance with appropriation rules and reduces illegal abstraction. Additional monitoring of resource use and user behavior may also be carried out by an *Ulu-Ulu* who is accountable to WUA members. In *Cialam Jaya* use monitoring was much stricter; uncertain water rotation schedules during dry seasons required farmers to also monitor other users at night to prevent detrimental interventions.

However, while use monitoring was effective within irrigation system boundaries, it was more difficult where water resources were affected by/dependent upon external factors; i.e. there is generally no robust system-wide water sharing system. For example, *Lapoa*, farmers could not control sediment impacts on river flows and canal capacity from upstream mining activity. Likewise, rice farmers in *Simbelai* and *Raraa* could not prosecute upstream pepper farmers whose illegal extraction reduced their water supply. Such significant water-affecting activities are beyond the scope of the local governance, requiring effective authority to enforce and prosecute (where relevant) infringements upon legal property rights. This leads us to our fourth proposition:

Proposition 4: *At WUA level, enforcement capacity and monitoring needs to be improved. Although farmer decisions to hold water at the head-end of irrigation system may not affect neighboring farmers in water-abundant areas, such decisions may be harmful to tail-end users as discussed in the DP 2a section. Affected users must be able to rely on effective monitoring and compliance mechanisms.*

6) DP4B: Monitoring of resources

Monitoring of resources is also a key issue in Indonesia, where flooding impacts can damage infrastructure or dry conditions can lead to reduced willingness by farmers to participate in system maintenance (Ma'mun, 2018). Typically, the head of a farmers' group, *Ulu-Ulu,* sluice guard (*Penjaga pintu air*) or Assistant Overseer (*Juru Pengairan*) will monitor infrastructure conditions and report defects requiring maintenance or rehabilitation to the Irrigation Overseer (*Pengamat*)—depending on the governance system in place. Resource monitoring activities are also required to evaluate water availability in the reservoir for allocation planning at the ID and WUA levels.

In conclusion, the capacity of WUAs and farmers to participate collectively in the process of resource monitoring and reporting suggests good coverage of this DP in existing institutions requiring no change at the WUA Level.

7) DP5: Graduated sanctions

Most WUAs apply penalties ranging from mild rapprochement of user infringement to strict penalties on users who take water out of turn. However, many farmers stated that their local methods were often ineffective for preventing repeat offending. Only water users in *Simbelai* reported effective sanctions, where famers that violated the operational rules were subject to severe penalties; that is, farmers who extract water out of turn are subject to the loss of watering access in the following planting season. The sanctions came into effect in 1999 and have only been tested once when the penalty was applied to a farmer that took water illegally in 2004. No other case has since been recorded, suggesting effective protocols. We therefore suggest our fifth proposition:

> Proposition 5: *Formal graduated sanctions which define penalties for low to severe infringements will be useful for preventing rule violations; particularly where those sanctions or penalties are transparent and apply to all users.*

8) DP6: Conflict resolution mechanisms

By contrast to sanction arrangements, conflict resolution mechanisms are more informal in Southeast Sulawesi irrigation systems, and usually WUA-facilitated. The term *musyawarah* is very common in Indonesia, used to describe informal methods or fora where leaders or trusted community elders debate and decide important issues. These fora are also often used to resolve water disputes within the community. More formal conflict resolution appears in the *Ladongi* ID where conflict resolution is usually facilitated by the Irrigation Overseer together with the head of village, a *Babinsa* (lowest military rank at village level), and the parties to the dispute.

Conflict with external parties often proved difficult to resolve, and in most of the villages mechanism to resolve conflict between cross-district or system farmers/WUAs were not present in the institutional arrangements. In *Roraya* for example, farmer protests against nickel mining activities affecting water and land quality had not been resolved during the time of this study.[3] Ideally, conflict resolution mechanisms should be present across all levels of management and easily accessed by users to resolve conflict among farming communities, between competing users, among irrigation districts, and between users and the environment.

[3] *Roraya* village was not part of our case study. However, some farmers in *Lapoa* were also members of the WUA in that village, and the impact of mining activities affected the irrigation water in both villages and the surrounding areas. This is also an example of how WUAs might join together in future to effectively resolve collective disputes.

This is especially urgent given expected changes to resource availability and variability in future.

<u>Proposition 6:</u> *Informal conflict resolution mechanism exists locally. What is urgently needed is a mechanism to resolve conflict at higher management levels.*

9) DP7: Minimum recognition of rights to organize

Indonesian Ministry of Public Works' Regulation No. 30/PRT/M/2015-*Article 9* specifically states that WUAs have the right and responsibility for: i) developing and managing tertiary irrigation systems; ii) maintaining effective and efficient irrigation development and management; and iii) approving the development, utilization and alteration of irrigation infrastructures using a participatory approach. This provides WUAs (and perhaps by association farmers' groups) with considerable capacity to organize with respect to irrigation system performance improvements. In support of this, WUAs also have a recognized right and responsibility to devise operation rules, such as water distribution and ISF payment mechanisms as discussed above.

However, the FGDs and other collected data suggested that WUAs can also be overlooked/overruled. For example, in *Simbelai* village, canal rehabilitation works have been carried out by consultants without prior discussion with WUA or the farmers' group. As a result, one part of the tertiary canal system has experienced rehabilitation with private gains for the related users, while other parts of the system also urgently needing rehabilitation have been ignored. This suggests that, while apparently well-resourced and authorized, WUA rights may be in need of further strengthening and protection—particularly in some areas of Southeast Sulawesi—consistent with the graduated sanction proposition incentives discussed earlier. We therefore offer our seventh proposition in support of that outcome:

Proposition 7: *Individual gains at the expense of others in a system can be avoided by giving WUA/farmers' group more authority (rights) to decide what they want to do within their irrigation system, and how they want it to be developed—as long as it does not contradict the system-wide rules or responsibilities.*

10) DP8: Nested enterprises

In complex and large systems, successful management governance activities are organized in multiple layers of nested enterprises (Ostrom, 1990). Cox et al. (2010) generalize this principle to include both vertical (between user groups and larger governmental jurisdiction) and horizontal linkages (between user groups themselves).

As discussed above, the water governance system in Southeast Sulawesi is nested, complex, and operates on the basis of operational size across central (>3,000 hectare command area), provincial (between 1,000 and 3,000 hectare command area), and district levels (<1,000 hectare command area). Further, water allocations for each irrigation district are decided at the river basin level which, again, may be assigned to a central, provincial or district government agency. Figure 3 details the structure of irrigation management in the study area. Development and maintenance of irrigation district systems down to primary and secondary canal level is the responsibility of the Ministry of Public Works (from central to district level), while responsibility for tertiary and quaternary canals currently falls under the (provincial) Department of Agriculture.

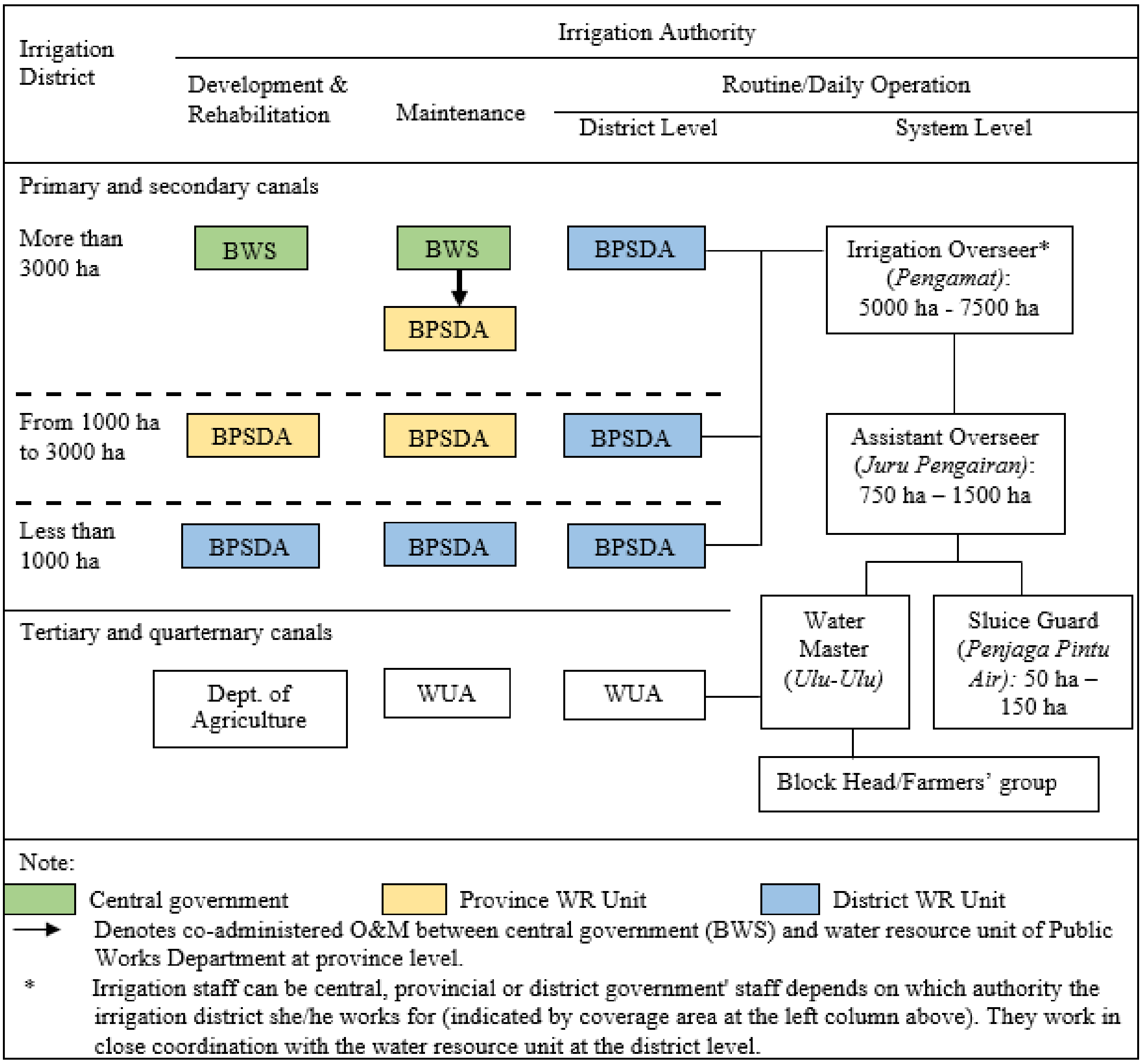

Figure 11. Structure of water management in public irrigation schemes

Indonesian water allocation in each river basin is typically planned annually by a technical team, and discussed within a *Tim Koordnasi Pengelolaas Sumber Daya Air* (TKPSDA) or Basin Council made up of stakeholders/water users including WUA representatives. For irrigation purposes, a cropping schedule and water distribution plan is also decided by the Irrigation Commission. The plan is then synchronized with the water allocation plan at basin level and executed by the Water Resource Unit of District Public Works, which coordinates down to the secondary and tertiary canal levels under close coordination with WUAs or farmers' groups.

From the above discussion, it is clear that the nested governance works in terms of irrigation provision. However, as outlined in the previous sections, other design principles are weak or absent at system-wide level. Some problems found in this study are related to cross-village systems that cannot be resolved internally by WUAs. Only the *Lapoa* WUA had strong inter-village linkages to facilitate sharing of limited water with three villages that had resulted in minimum conflict for more than 20 years. This brings us to our final proposition for institutional change:

> Proposition 8: *In the absence of system-wide rules, WUAs need to strengthen the horizontal linkages between them, to share water more equitably and increase their bargaining position when facing current/expected impacts of other user activities that are directly/indirectly relevant to the irrigation system.*

3.5 Discussion and Conclusions

In this paper we have sought to draw lessons from local level institutional assessments to provide insight on wider system change that may facilitate community resilience in the face of dynamic supply and demand changes. An evaluation of local irrigation systems using a modified version of Ostrom's design principles is useful for identifying current institutional arrangements at local levels, how those institutional arrangements incentivize/disincentivize individuals to participate in collective operation and maintenance of irrigation systems, and whether those institutions will enable sustainable performance and productive future water use in the face of dynamic change.

The timing for institutional review and reform is ideal at present. Following the unsatisfactory results of the IOMP in 1987, Presidential Instruction Number 3 in April 1999 set out irrigation reforms with the redefinition of irrigation institutions as one of its five principles. This principle signified a need to grant farmers more authority as decision-makers on irrigation system management in their respective area. However, further reforms via Water Resource Law No. 7 in 2004 have been criticized by experts and NGOs as an attempt to recentralized irrigation system management (Pasandaran, 2015; Suhardiman, 2013). While Water Resource Law No. 7 was cancelled in 2015 by *Mahkamah Konstitusi* (the Constitutional Court) under a view that the law was prone to multi-interpretation that could harm public rights to access water (Al'Afghani, 2006; Pasandaran, 2015), a current lack of legal frameworks makes existing rules at the system level more difficult to enforce, as evidenced by our case study. With respect to the objectives of our study, we have outlined a series of propositions for specific institutional change in Southeast Sulawesi that may improve irrigation system performance and sustainability at local levels, in line with Ostrom's design principles. However, if we reflect on those suggested changes there are several specific changes that should be discussed further.

Our analysis has highlighted the importance of clearly defined boundaries, which is also identified as a necessary (but insufficient on its own) condition for robust irrigation system outcomes (Ma'mun et al., 2019). The rationale behind this requirement according to Ostrom (1990) is to prevent over-abstraction and free-riding problems. However, as we have shown here, specifying authorized users and the physical boundary of the resources is not enough. Limits to development at the system-wide level need be established, and an offset (reallocation of rights at the margin) rule introduced for successful future management—especially with respect to dynamic change. This will provide institutional certainty about the rules for managing supply uncertainty from basin level down to the local irrigation systems. In Southeast Sulawesi, while resource and use boundaries are mostly observed by internal (and some external) users, villages commonly reported problems linked to (mis)appropriation and provision issues where users had different access to water, and endured unequal risk-sharing of water shortages during dry periods. This led to agreed or (more typically) passive disengagement by farmers from operational and maintenance contributions, and a greater requirement for government subsidized O&M programs—despite policy to reduce financial burdens on taxpayers by transferring irrigation system management to WUAs. The availability of other sources of water may also reduce water users' participation in collective action (Tang, 1992) as seen in *Raraa*.

When farmers access different sources of water it is difficult to discern who then has a responsibility for contributing toward system maintenance. While requirements to seek water access elsewhere might be reduced by current storage construction projects, infrastructure itself cannot guarantee the sustainability of the irrigation system, and high canal distribution performance can only be cost-effectively achieved through farmers' cooperation toward maintenance (Lam and Ostrom, 2010). We have shown that equal capacity to access water and appropriate incentives to share the costs and risk of water access among farmers/WUAs will improve the probability of collective action; a finding echoed by other studies (Baland and Platteau, 1999; Janssen et al., 2012; Kosanlawit et al., 2017). But it will also be important to incorporate and collectively manage relevant external users, such as pepper farmers in *Simbelai* and *Ladongi*, as members of the WUA to avoid free-riding, collective participation toward O&M, and equitable cost-sharing with other WUA members (Vermillion et al., 2000).

A second major issue was external impacts on current water users, and effective authority to enforce, protect and sanction violations against 'legal' water use. As revealed by our research, some external actors or activities that have direct impact on water users' appropriation and use status in modern irrigation systems may be challenging to sanction—but the same can be said of Indonesia's older irrigation systems under dynamic change impacts to supply and demand. In Indonesia, while water allocation for basic human needs and small holder farmers are supposed to be prioritized, farmers tend to lose when facing a bigger player in the economy (e.g. Komakech et al., 2012; Levine et al., 2007). Examples of this have been reported in Bali (Cole, 2012; Cole and Browne, 2015; Strauß, 2011) and West Java (Hadipuro et al., 2014; Kurnia et al., 2000) where tourism and manufacturing industries were given precedence over agricultural sectors. In this study mining provides an additional example. Mining activities have increased significantly in the last ten years and, without proper management, the associated negative externalities could increase similar to issues reported in the Philippines (Castañeda and Bhuiyan, 1993). Shifts in allocation priority in Bali have put the long tradition of *subak* collective systems at stake (Strauß, 2011), which has important implications for modern irrigation systems of Indonesia with reduced collective foundations. As a response to such threats in a forestry management context Gautam and Shivakoti (2005) highlight the importance of strong property right, monitoring and sanction institutions providing local communities with capacity to monitor and exercise effective restrictions and/or injunctions to 'illegal' use. We find similar requirements for irrigation management in Indonesia, especially given the complex and often ineffective nature of central and provincial authority to deal with matters of conflict and resource misappropriation.

Finally, farmers and their irrigation systems exist in a complex environment. External factors that affect water flows will naturally affect the quality and quantity of resources supplied to the tail-end of irrigation systems. Our propositions to improve institutional arrangements for sustainable irrigation in Southeast Sulawesi signify a need for hierarchical arrangements to foster the emergence of locally defined solutions that tend to naturally accommodate the total length of irrigation systems. Our findings align with Sjah and Baldwin's (2014) recommendation for multi-nested governance of water management in Lombok, another province in eastern Indonesia. Similarly, Suhardiman and Giordano (2014) observe that irrigation sector reform can be achieved by multiple levels of governing agencies, where they suggest beginning with farmer-agencies based on a case study in Kulon Progo District in Yogyakarta. We would argue such approaches might help to resolve underlying tensions and complexity associated with sustainable management requirements in the face of dynamic supply and demand changes.

Collective action is important for the future sustainability of the irrigation systems (Baldwin et al., 2018; Meinzen-Dick et al., 2002). However, as we have seen in this study, system-wide rules defined by central/provincial governments could either facilitate or downgrade local collective management. To date, irrigation reform in Indonesia continues under an integrated water resource management (IWRM) framework with the (central) Ministry of Public Works as the leading actor. Indonesia has initiated legal frameworks for extending water use rights to farmers through relevant WUAs, but much more work is needed to create the needed institutions that will effectively protect those rights, and provide resilience in the face of future change. While we have outlined and justified specific changes in Southeast Sulawesi that could be trialed immediately, with lessons for other areas, future research is needed to develop and implement a nested framework that could facilitate local institutions to grow in their capacity to manage current supply/demand constraints and, at the same time, provide opportunities for other economic sectors to grow.

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Contribution to the Paper	Conception and design of the study; acquisition of data; analysis and/or interpretation of data; drafting the manuscript; and revising the manuscript critically for important intellectual content.		
Overall percentage (%)	65%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	21 June 2020

Co-Author Contribution

By signing the Statement of Authorship, each author certifies that:

vii. the candidate's stated contribution to the publication is accurate (as detailed above);

viii. permission is granted for the candidate in include the publication in the thesis; and

ix. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution

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Chapter 4: Putting Ostrom's nested principle first: Lessons from water governance in Southeast Sulawesi

Abstract

During the last three decades, many studies have provided empirical support of the relevance of the design principles (DPs) proposed by Elinor Ostrom as a way to examine the robustness of CPR institutional arrangements. Amid this support, a question has emerged regarding the DPs' relevance to the analysis of complex, large-scale CPR systems—especially those involving the management of large, interconnected water resource systems. Ostrom's last principle, her nested enterprises, requires large and closely-connected resource governance arrangements to be organized in multiple nested layers. In this paper, we argue that by putting Ostrom's nested enterprises principle first, much more precise guidance as to how best to apply her other principles emerges. Some require application at all levels in the hierarchy, while others apply only at some levels. The resultant narrative is richer and better recommendations for the improvement of governance arrangements tend to emerge. We test our argument in Southeast Sulawesi Province, Indonesia, through a transaction cost lens. The resultant regional narrative produces a new set of recommendations for the improvement of water governance arrangements in Indonesia.

Keywords: *water governance, institutional arrangement, design principle, transaction cost economics, Ostrom*

Highlight

- We apply the re-ordering of Ostrom's design principle to examine water governance.
- We evaluate the design principles using transaction cost economics theory
- We focus on hierarchical institution design arrangements.
- Additional emphasis on boundary definition for efficient development is needed.

4.1 Introduction

Over the last few decades, a rapid increase in competing demands by agricultural, urban, and industrial use(r)s has tested the institutions that manage scarce water resources. Designed and implemented under different demand/supply conditions, many institutional arrangements are failing to cope with a rapidly changing and dynamic environment. As current water institutions struggle to cope with these new conditions, crisis management is becoming increasingly common (Garrick et al., 2020). The successful management of a crisis can produce political benefits, yet tends to entail a high cost for society. The alternative approach is to seek ways to transform older regimes into ones that are sufficiently robust to facilitate the management of scarcity (Young, 2014, 2019).

Building robust water sector institutions is a continuous and difficult endeavour (Ostrom, 1993). All governance contexts have examples of institutions that have withstood the test of time and examples of others that have failed. Moreover and to date, variation across and within water governance contexts has prevented the development of a single blueprint for managing water resource systems. As argued by Ostrom, however, underlying principles can be derived from an examination of arrangements that have brought long-lasting success in the management of common-pool resources (CPRs). Ostrom (1990) summarized these underlying principles of self-governing institutions into eight design principles (DPs), which have contributed greatly to CPR theory and application. Ostrom (2008) argued that, when and where applied properly, these DPs increase the probability of the emergence of robust CPR system governance outcomes. A vast quantity of literature has examined CPR case studies in which the DPs have been employed, and have played an important role in attempts to increase the effectiveness and robustness of self-governing institutions. Such studies have evaluated whether the presence of Ostrom's DPs influences the effectiveness of institutions, and hence their capacity to withstand the test of time. Ultimately most, if not all, of Ostrom's DPs have proved useful for describing robust CPR systems (Baggio et al., 2016; Cox et al., 2010)).

Studies using CPR theory have also, contributed to myriad policy-making insights that recommend the transfer of CPR management responsibility to local users (Agrawal, 2001; Carlsson & Sandström, 2008). Many of these recommended institutional transitions, however, have not resulted in the desired outcome (Meinzen-Dick et al., 2002). Kerr (2007) reasoned that, while complete replicability is limited to a relatively small number of cases, it can be observed that local institutions have restricted capacity to resolve trade-offs between local and higher-level needs, which tends to constrain opportunities for collective action. Additional critiques of Ostrom's DPs observed that many previous studies have focused on relatively simple, local-scale institutions involving single-use resource management regimes that are isolated from the larger complex and dynamic environment surrounding them (Agrawal, 2001; Berkes, 2006). When an interaction between resource units exists across multiple scales, institutional organizations, and jurisdictional boundaries—and is coupled to diverse user groups with different types of rights to access available resources—the study and identification of principles driving robust self-governing institutions has proven to be difficult (Berkes, 2006; Evans et al., 2014; Fleischman et al., 2014; Young, 2002). Thus, a scaling-up of Ostrom's DPs to evaluate and analyze the effectiveness of large-scale resource institutional systems has been contested (Young, 2002). This is especially the case with large water resource systems where impacts can be unidirectional, and downstream users have little opportunity to control upsteam users unless these issues are equitably and efficiently managed at higher levels.

Critically for this study, some researchers believe that further research on the development of the nested principle is necessary. For example, Fleischman et al. (2014) argue that the complexity of large-scale CPR systems renders difficult, if not impossible, the development of "bottom-up" self-governing institutions, which is central to Ostrom's thinking.

The alternative, which we examine, is to devote attention to such arrangements in national and provincial laws and regulations as a primary, rather than final, process. We seek to further test this premise using transaction cost analysis as a basis for placing nested institutions at the top of Ostrom's list in an Indonesian water resource management case study. Within a broader social, economic, and environmental framework, we then assess DP capacity to manage resource allocation under existing rules, as well as periodic requirements to reallocate resources between sectors (robust arrangements) during scarcity.

4.2 Putting Ostrom's nested principle first: justification of the framework

As stated above, some studies that have applied Ostrom's DPs provide insight into how their ordering—with nesting arrangements considered last—has constrained understanding by frequently isolating local governing institutions from the wider environment and resource system context. We argue that, by putting the nested enterprises principle first, the remaining DPs will be better framed to encapsulate regional- (local-) level institutional arrangements. Earlier consideration may also better guide the design and structure of hierarchical management rules to take maximum advantage of the characteristics of self-governing arrangements, which inspired Ostrom (1990, 2010) to propose them as a way to move beyond the tragedy of the commons. This argument is further justified as follows.

First, CPRs exist in multiple layers across complex systems that affect self-governing institutional performance (Agrawal, 2001; Berkes, 2006; Young, 2002). Ostrom (1990) demonstrated that local communities can regulate themselves and create a common property regime to ensure that co-owners' expectations of right to access resource units are met. These communities, however, are particularly vulnerable to external pressures—especially scarcity-related pressures that have not been part of their historical experience (Berkes, 2006). Once scarcity, whether periodic or continuous, becomes part of the new norm, new pressures emerge.

Routine shifts in supply have to be accommodated in a dynamically challenging manner. This includes changes in demand for access as a result of changes in product prices (and other substitute or complementary inputs), and technology changes. These changes are all complicated by a tendency for rural-urban migration and population increases. Anticipated and actual climatic changes are also challenging traditional decision-making processes and/or accepted rules of behavior. These factors mean that stationarity can no longer be used as a guiding concept. To succeed, either local resource users and managers need to be protected from these changes made elsewhere in the system, or empowered to adapt in a manner that is socially and economically acceptable.

From an institutional design perspective, care needs to be taken to understand which decisions are best left to the individual, which are best managed by the local community, and which decisions have to be taken—or are more effectively taken—at a higher (nested) level. In this scope, the role of the state is critical, as the guardian of natural resources has the ultimate authority to define how rights are defined and issued, to grant these rights, and then enforce compliance. In well-designed systems, some of these authorities can be passed to or shared with local institutions in the pursuit of effectiveness, equity, and efficiency benefits (Ojha, 2014; Sarker, 2013). Others, such as the form that the rights might take and how they assign responsibility for managing changing conditions, need to be managed centrally so that local and regional communities have the power to manage change via mechanisms that can cope with alterations to supply and demand. This suggests a requirement for early, if not primary, consideration of the nested enterprises as a basis for working out how to apply Ostrom's other principles. The insight offered in this paper is that it is critically important to work out where in the nesting hierarchy to establish authorities, whether or not to establish top-down or bottom-up subsidiarity arrangements, and how to facilitate reviews at different scales and layers in the hierarchy.

Second, it is clear from the above that many CPR challenges are beyond the capacity of local community institutions to manage (Gautam & Shivakoti, 2005; Ojha, 2014). Conceptually, standardized nesting frameworks can be used to enable the better management of scale-related complexities (Lacroix & Richards, 2015; Tyson, 2017), especially when, as we argue here, local communities may be empowered to thrive because the form of the hierarchical or nesting rules and governance arrangements is robust. For this to occur, we argue that nested enterprise arrangements need to be addressed first. With this outcome in mind, Bray (2013) has stated that the focus of Ostrom's DPs must be incorporated in national regulations, so that local institutions are empowered and designed to facilitate equitable, efficient and environmentally sustainable forms of adjustment in a dynamically complex, ever changing CPR system. This would suggest a dominant role within the DP ordering for nested enterprises governance institutions, and we would agree.

We find further support for our nested-dominant institutional argument in transaction cost economics (TCE) theory. Williamson's (2000) TCE states that we should first establish the formal rules and play of the game (L2 and L3 in Figure 1) before (re)allocating resources within the lowest levels of economizing at more frequent intervals (see L4 in Figure 1). According to Williamson (1985), TCE focuses on ensuring that the institutional environment is suitable, and implementing governance structures that align with the dimensions of transactions to create credible commitment and security of expectation by actors operating in the lower levels of the economy. For local communities and the individuals found at these lower levels, this approach provides an incentive to grow their capacity and confidence to manage resources, which can subsequently also be consistent with system-wide natural resource management objectives.

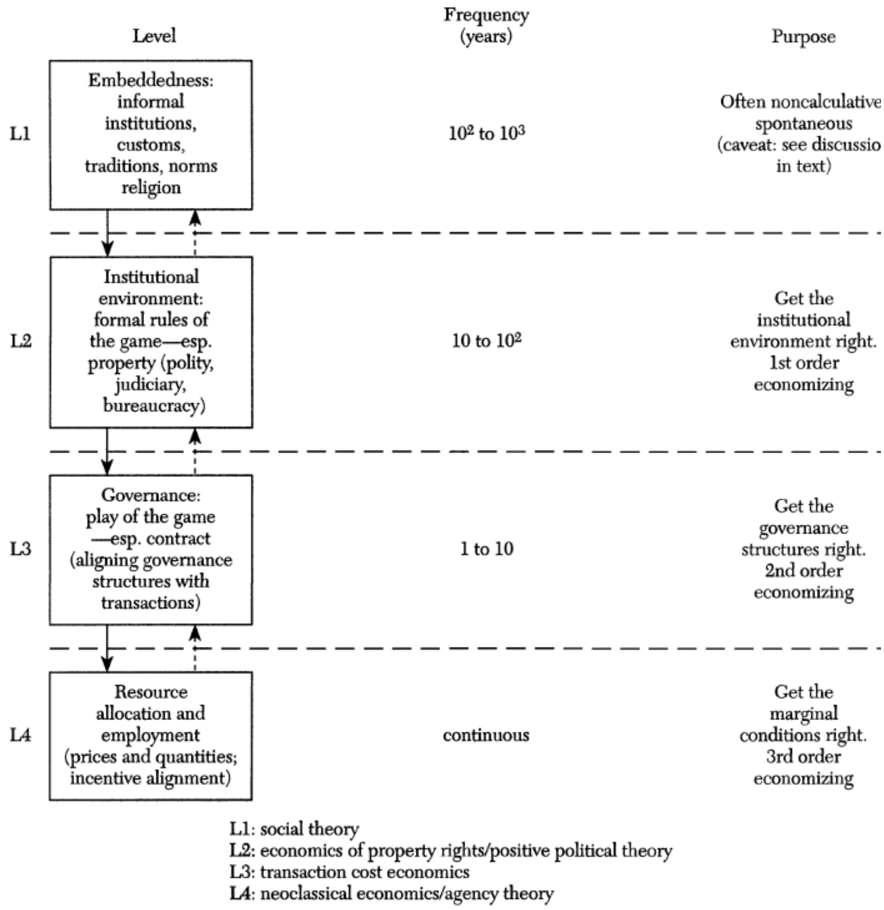

Figure 12. Economics of institutions (source: Williamson, 2000)

Notably, Williamson (2000) stated that the capacity for lower-level institutions to affect change to the higher levels after establishment is challenging (denoted by the dashed upward arrows in Figure 1) and requires significant time, investment, and effort to achieve. We would add, also, that it requires great clarity of thought and development of a compelling narrative. This again highlights to us the relevance of focusing on and correctly ordering the sequence in which DPs are addressed. Thus, we hypothesize that a reordering of Ostrom’s DPs and, in particular, the placement of her nested-enterprises principle first can be expected to increase the probability that widespread consideration of them will improve the management of water and other common property resources. To test this hypothesis, we examine the current institutional arrangements of the water sector in Indonesia, focusing on the Southeast Sulawesi

Province. In the following discussion, we seek to identify constraints to the design and operation of robust systems, and potential institutional arrangements to resolve them.

4.3 Background of the study area

4.3.1 General overview of water governance in Indonesia

Water governance in Indonesia provides a useful example of the nature of nesting issues in a country involving at least three layers of government and many large basins and aquifers. Early Indonesian water governance models focused on small-scale, simple hydraulic systems under traditional cooperative institutions. Typically, these institutions involved relatively high levels of organization at the local level and careful monitoring of performance, such as in the *subak* system in Bali. Colonial influences stemming from the Dutch East Indies intervention period led to changes in the traditional system and the introduction of modern irrigation practices. Water was relatively abundant and most systems were run conservatively so that scarcity was either not, or rarely, an issue.

Recent developments in the form of increased local demand, changes to historic supply conditions, decreased local contributions to operating costs and maintenance, poor system performance, and increasing complexity as more users enter and compete for access to a previously abundant resource is testing the robustness and resilience of these systems (Bruns, 2004; Sumaryanto, 2012). All of these factors have worsened under the hydraulic mission adopted after the colonial era, which has tended to lock in the perception of defferend maintenance as the core problem and worsen irrigation performance (Suhardiman & Mollinga, 2012). This perception reinforces a justification of the need to focus on physical infrastructure development (Bruns, 2004; Suhardiman & Giordano, 2014) rather than a review and modification of institutional arrangements. One response to these issues, the Irrigation Management Transfer program in the late 1980s for example, failed to increase farmers' participation in irrigation system monitoring and maintenance (Oad, 2001). Further, despite targeting smallholder irrigated agriculture as a priority for water allocation, in practice, farmers' access to water has been set below that of the industrial sector in many areas. This has allowed industrial users to increase the proportion of the available water that they take (Cole & Browne, 2015; Kurnia et al., 2000) without compensating the farmers for their associated losses. That is, while official policy statements give priority to farmers, in practice, industrial and urban water users are given first access – especially when they are located upstream of irrigated landscapes.

In response to increasing recognition of the need for reform, a narrative centred around "integrated water resource management" has been articulated by the Central government. Thus, over the last three decades, institutional reform has gradually occurred, most notably marked by the promulgation of the National *Water Resource Law* (WRL) *No. 7* in 2004. However, institutional reform consistent with first-order economizing (L2 in Williamson's framework, including polity, judiciary and bureaucracy) remains largely theoretical and prescriptive (Fulazzaky, 2014), and has resulted in increased uncertainty for managers, investors, and users. For example, after being in place for just 10 years, the National *WRL No. 7* was annulled in 2015. Since then, numerous Government Regulations have been promulgated, subsequently annulled, and replaced with yet another attempt to lock-in a sensible reform pathway, illustrated most recently by the passing of *WRL No. 17* in October 2019.

4.3.2 Case study area

Consistent with the messy and highly uncertain processes described above, over the last 20 years water governance in the Southeast Sulawesi Province of Indonesia has experienced significant change in terms of water resource use and economic development. Southeast Sulawesi has two main seasons: a rainy season that typically occurs from April to August and a dry season that occurs from September to January. Average annual precipitation is 2,000 mm per year and there are five main river basins or “Wilayah Sungai” (WS). Two of these river basins—the WS Lasolo-Konaweha and WS Towari-Lasusua—are managed by Balai Wilayah Sungai (BWS) Sulawesi IV, which as a result of National legislation is a river basin organization with direct access to the Central Indonesian Government. The Central Government’s role in these two river basins stems from their trans-boundary nature—that is, they extend across three provinces: the Southeast Sulawesi, Central Sulawesi, and South Sulawesi. Located within the Province, the WS Poleang-Roraya, WS Muna, and WS Buton are managed by Bidang Pengelolaan Sumber Daya Air (BPSDA) or the Water Resource Management (WRM) agency, which is part of the province’s Department of Public Works.

All these mainland river basins have somewhat achieved second-order economizing strategic water system-wide resource plans, or *Pola* as they are known locally. The development of plans is now underway for two other river basins on the islands of Muna and Buton. Among these five mainland river basins, WS Lasolo-Konaweha is the largest and most strategically important for provincial development, covering 1,361,068.34 ha in total, of which 94.74% is located in the Province. While first-order economizing arrangements appear to be present, it is less certain whether the second-order contracting arrangements necessary to enable the reallocation of water entitlements have been put in place. For many years, irrigated agrilcutre enjoyed relatively uninterrupted water supply. But growth in mining activities, and increased commercial agriculture, have placed pressure on land and water as principal inputs to production, leading to increased tension and conflict among user groups. A gold mining boom in Bombana regency (akin to district or local area in Indonesia), located in WS Poleang-Roraya in 2008, has also caused environmental degradation and disrupted agricultural sectors in the area (Ma’mun, 2016). In more recent years, this conflict has spread to other regencies as further economic development has occurred.

These characteristics, particularly those of the WS Lasolo-Konaweha River Basin, suggest that the Southeast Sulawesi Province offers an excellent example of a complex CPR resource that can be used as a case study to consider first-ordered nested enterprise governance arrangements. Our focus is on institutional robustness – the capacity of a system to efficiently, equitably and sustainably manage changes in supply and demand conditions and to function well during times of extreme stress and supply uncertainty (Young 2014). Robust institutional structures are designed to enable effective management of the full range of possible futures, and particularly can be expected to perform well during times of high pressure. We consider that this requires full consideration of scale and scope, as set out in our proposed reordering of Ostrom's DPs. The following section details the methods and data used to conduct this analysis.

4.4 Material and methods

4.4.1 Analytical framework

As indicated above, we combine Ostrom's DPs and Williamson's TCE in the analytical framework. Following Commons (1932), Williamson (1985, 2000) uses transaction costs as the basic unit of analysis in the TCE framework. According to Commons (1932, p. 13), water allocation can be classified as a **rationing transaction**, "on account of expected scarcity, thus prescribing who may make use of them, and when." In the water sector, arrangements used to prescribe who may access water – when, where, and in what quantities – form key elements of the institutional design.

Ostrom (2008) argued that institutional design is the result of rational choice. However, this rationality is bounded by incomplete information or limited human cognition to process all the information of the complex system they are within (Simon, 1972). This bounded rationality assumption, coupled with opportunism (i.e., self-seeking interest with guile), may create a hazard in which the operational rules are no longer respected – especially among those located upstream – with the result that conflict emerges, and socially sub-optimal outcomes result. We use TCE to further understand the robustness of water allocation systems, including assessment of the question of whether the current institutional arrangements align with the arrangements used to create *order*, mitigate *conflict*, and achieve *mutual gains* (Williamson, 2000).

To understand the complexity of institutions and their interaction in the Indonesian water sector, we first created a general water governance framework (Figure 2). This framework does not provide an exhaustive list of all attributes related to the governance of water resources; rather it should be seen as an example of the different aspects that interact with each other and influence the status of water supply and demand and the outcomes it may achieve. In effect, this highlights the complex nature of water governance arrangements in most contexts, where the way that water is allocated to different uses and users will depend on the nature of the socio-economic objectives held for the water resource and the regional economy.

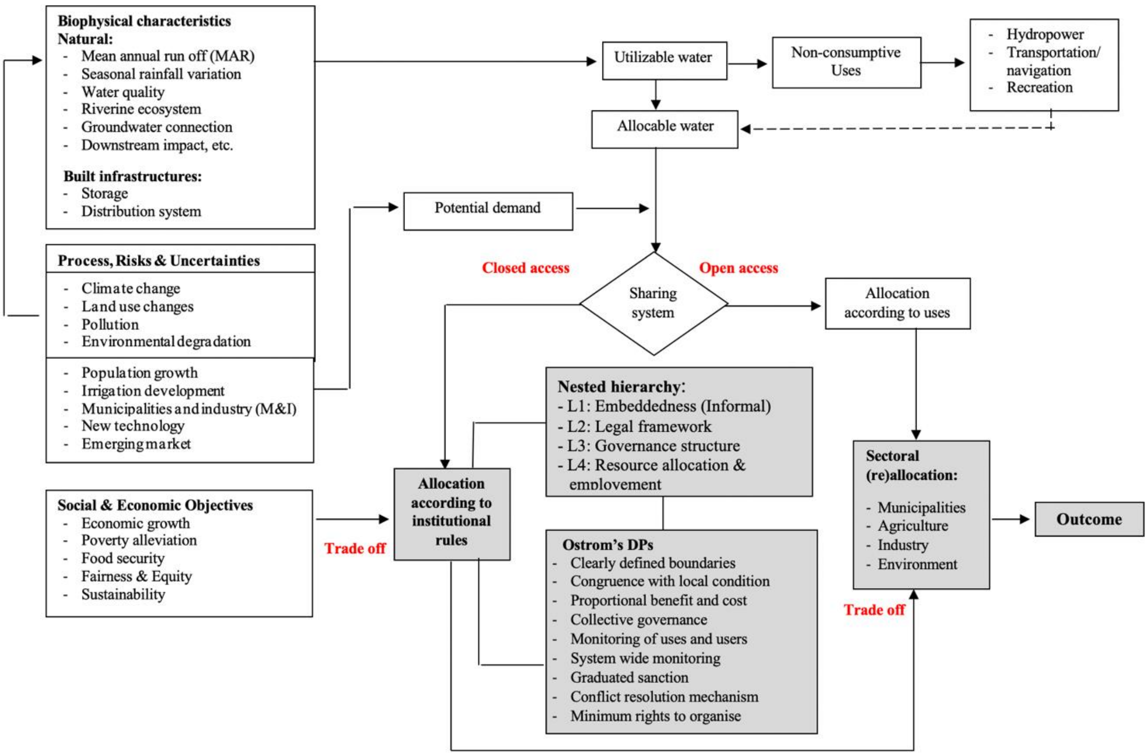

Figure 13. General framework for water governance

Figure 2 also draws links between institutional arrangements designed to manage access to abundant water resources and those for which access is, or should be, "closed"; that is, whenever someone wants access to a larger share, someone else has to accept a lesser share. The shadow boxes in Figure 2 indicate the nature of the links between Ostrom's DPs and Williamson's TCE frameworks.

In Indonesia, the water resource is under the control of the state and legislation requires that water must be used for the greatest benefit of the people.[4] Recognizing that demand tends to outgrow supply, the law also requires that water be managed by considering and pursuing a balance of social, environmental, and economic functions of water in an integrated, sustainable, and environmentally sound approach.[5] When water is scarce and, in particular when the nature of this scarcity changes, trade-offs need to be made between objectives in a manner that has consequences for competing users.

Having determined our assessment framework, we then developed a checklist of DPs to determine which attributes were subordinate to the (now) dominant *nested hierarchy DP*. Using Williamson's TCE as a guide, this resulted in five broad governance arrangements that could be grouped as follows:

- first-order institutions for (1) legal frameworks
- second-order institutions for (2) system-wide planning and (3) sub-system arrangements
- third-order institutions covering (4) local management arrangements and (5) individual users. The local management (WUA) was included based on the regulation that smallholder farmers have the right to use water through their WUA.

[4] Chapter 3, "State Control and People Right to Water," article 5 WRL No 17 in 2019.
[5] Chapter 5, "Water Resource Management," article 21(1) and 21(2) WRL No. 17 in 2019.

Across these (now) dominant nested institutional types, we then itemized and assessed both the presence and clarity of the other DPs to highlight gaps—and positive institutional outcomes—at scaled management levels to identify institutional reform opportunities at governance levels. This also enabled us to consider institutional capacity to deal with scale complexities and interconnectedness, as suggested by Hagedorn (2008), where the configuration of these arrangements could be expected to increase robustness. Finally, with respect to outcomes associated with capacity to adjust, we considered Williamson's (2000) transaction attributes (i.e., asset specificity, uncertainty, and frequency) as a test of governance structure alignment with allocation objectives to further evaluate institutional appropriateness.

4.4.2 Data collection

Given that the aim of this research was to more fully understand the relevant institutional and contextual conditions with respect to how access to any water resource should be allocated, managed and used we relied mainly on qualitative methods. The overarching objective for this data collection strategy was to collect information on institutional capacity to cope with changing water demand in the area and, more recently, manage the increasingly uncertain future water supply conditions.

Following Yin (2011), we used a combination of interviews, focus group discussions (FGDs), a stakeholder workshop and document inspection to enable us to capture the diversity of sub-basin water resource users and the complexity of water allocation (sub)-systems. The methods used also served as a means to triangulate the information. The process commenced with a desktop review of key documents on Indonesian water law, government regulations related to water management, and strategic water resource development plans managed by the Central and Provincial Governments. The desktop review included research articles in the period following the 2004 promulgation of WRL *No. 7* to identify any relevant research and secondary study findings of interest to our work. In addition, we conducted a series of personal interviews, a stakeholder workshop, and six FGDs in the period spanning August to October 2017. The fieldwork interviews were undertaken with four officials at BWS Sulawesi IV, six officials from the Water Resource Division at provincial and regency levels, a staff member from the Water Division of the Agricultural Department, three irrigation district staff, and the head of a local WUA (GP3A). Our study also focused on three regencies: Konawe and Kolaka Timur, which are part of Lasolo-Konaweha River basin, and Konawe Selatan, which is part of both the Lasolo-Konaweha and Poleang-Roraya river basins. These are the main areas of economic development and activity. A semi-structured interview format was used. Each interview lasted between one and two hours and covered topics including water resource and irrigation management in each of the respective areas, water allocation mechanisms, and the nature of problems or conflicts associated with the water resource. Another round of interviews was conducted in June 2019 to follow up on any issues requiring further clarity or insight.

The Department of Research and Development of Southeast Sulawesi facilitated a one-day workshop with 18 stakeholders. These included officials from BWS Sulawesi IV; staff from WRM at both provincial and regency/district levels; and staff from the Forestry Department, Watershed Management Institute, Environment Department, and Regional Planning Department. Finally, in order to enable consideration of the diversity of water resource conditions and the state of WUA development and related institutional arrangements, we selected two villages from each regency listed above to conduct FGDs in a local farmer's house. Five to eight farmers participated in each FGD, which lasted for an average of two hours. The FGDs were aimed at understanding the realities of water allocation regimes in the context of different farming operations and areas.

4.5 Results

Initial output from the data analysis was an institutional map of current water governance arrangements in the case study area (Figure 14). This map attempts to reveal the nature of the hierarchial structure of surface water allocation and management arrangements in WS Lasolo-Konaweha, under BWS Sulwesi IV regulations. The structure generally focuses on two properties: (1) responsibility for water allocation and (2) responsibility for irrigation infrastructure. In the case study area, there is a clear hierarchy of institutions with nested properties. All decisions related to water resource development and allocation are authorized by the Central Government through the Directorate General of Water Resources (Dirjen SDA). Governance structures in WS Poleang-Roraya are similar; although, in that case, the Provincial Government sits atop the structure (BPSDA-P) for water allocation decisions, where the "-P" designates provincial level. Therefore, depending on the type of river basin, water allocations are decided by either the Central or a Provincial government.

By contrast, responsibility for irrigation infrastructure decisions sits across all three levels of government (Central, Provincial and regency; for example, the BPSDA-R). Each irrigation district uses primary-, secondary-, and tertiary-level canal systems to deliver water to users. At the lowest level (tertiary), only the first 50 meters of canals are maintained by the relevant government authority; beyond that point, they become the responsibility of local WUAs, including cost-recovery. Even so, each WUA needs permission from the relevant authority if they wish to modify their tertiary canal. Finally, at the lowest levels of organization, we find individual farmers, who are encouraged strongly to belong to a WUA. All other licensed water users (e.g., mining companies) are under the same pressure. The institutional map highlights the complex, nested and hierarchical nature of institutions in the case study area and the importance of hierarchal or nested arrangements in determining governance options at lower (e.g., reallocation transaction) levels.

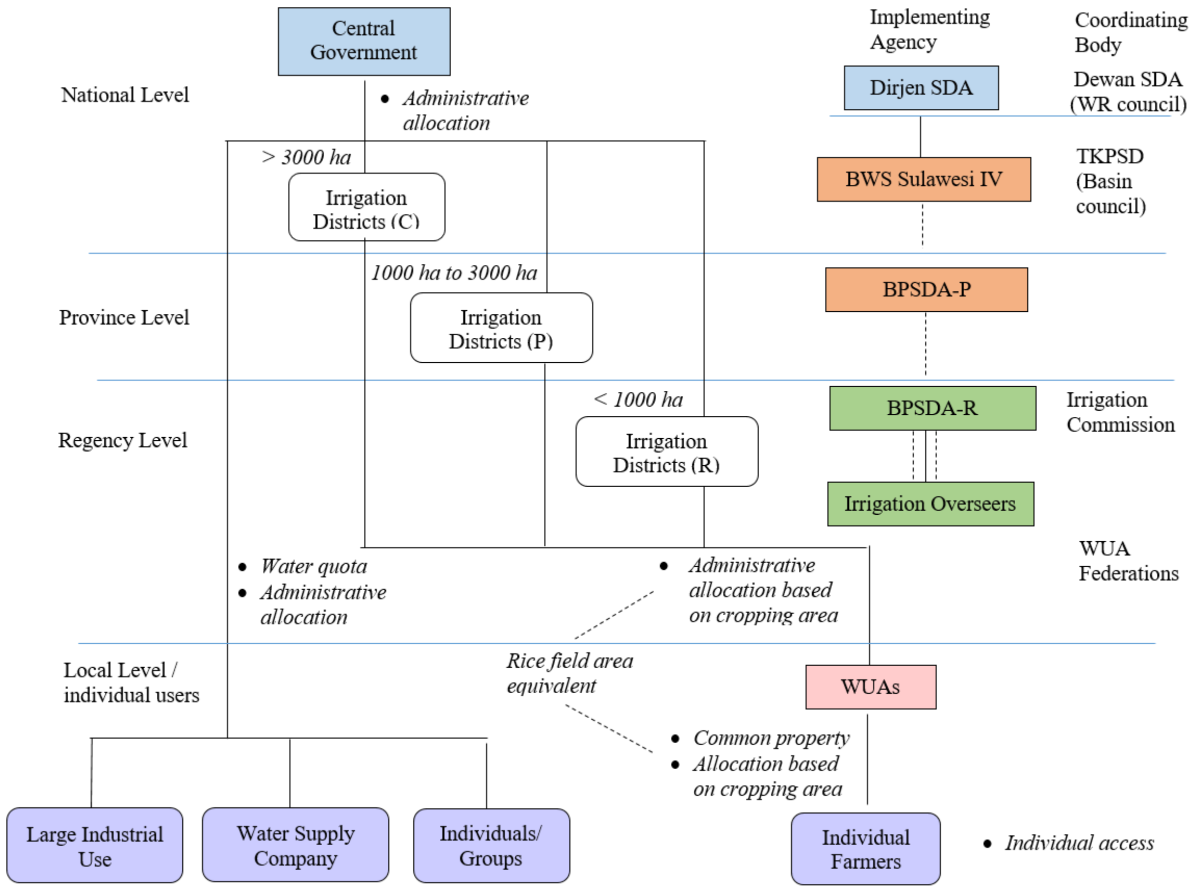

Figure 14. Hierarchical arrangement of water governance in WS Lasolo-Konaweha

We next turned to our evaluation of Ostrom's DPs across these nested institutional levels and roles (Williamson's first-, second-, and third-order economizing properties) to identify gaps in the governance structure (Table 1). A brief explanation of each DP attribute, and the evaluation outcome, is provided in the following sections.

Table 14. Checklist for evaluation of Ostrom's design principles

Design principles	Legal framework	System-wide plan	Sub-system arrangement*	Local management arrangement*	Individual users
Clearly defined boundaries					
- For entire connected water resource	+	++	+	+	NA
- Of the boundary for each component	NA	++	++	++	++
- Of the administrative structure	++	++	++	++	NA
- Clearly defined water-sharing framework	+	0	0	0	NA
- Clear sharing priorities and obligations during shortages	+	0	0	0	NA
- Clear flood risk-management rules	NA	+	+	0	NA
Congruence with local social and environmental conditions					
- Protection of minimum flow to the end of the system	+	+	+	–	NA
- Clear limit of water abstraction	NA	0	+	+	+
- Efficient and equitable adjustment mechanism:					
• Within each component	0	0	+	+	NA
• Between components	0	0	0	0	NA
• Within administrative regions/units	0	0	0	0	NA
• Between administrative regions/units	0	0	0	0	NA
Proportion of benefit and cost					
- Budgeting rules and process	NA	++	+	+	NA
- Budgetary independence and accountability	NA	++	+	++	NA
- Beneficiary-pay requirement	+	++	0	+	+
Collective governance					
- Stakeholder/user participation	+	+	+	++	+
- Effective representation	+	+	+	+	+
- Timely access to information	NA	+	–	–	+
Monitoring of users					
- Timely monitoring and use reporting	+	0	+	+	++
- Timely status reporting	+	0	+	+	+
Monitoring of resources					
- Of hydrological condition and status, *including risks*	NA	+	+	+	NA
- Of infrastructure condition and needs	NA	++	++	++	+
- Timely data reporting, access, and information review	NA	++	++	++	+
- Of water supply and quality-affecting activities	++	0	+	+	+
- Robust accounting rules (return flow)	0	0	0	0	NA
Graduated sanction					
- Clear graduated sanctions for all types of infringement	+	0	0	+	NA
- Transparency of sanction enforcement	NA	0	0	0	NA
Conflict resolution mechanism (CRM)					
- Low-cost and rapid CRM	++	+	+	++	++
Minimum rights to organize					
- Minimum right to organize	NA	++	+	+	NA
- System-wide accountability	++	++	+	NA	NA

Notes:

++ = the rule exists and is clear NA = not applicable
+ = the rule exists yet is not clear (or weak) – = not available
0 = the rule is nonexistent

* Sub-system arrangement is observed at ID level, and local management is at WUA level.

4.5.1 DP1: Clearly defined boundaries

DP1 requires the following: (1) "User boundaries: clear and locally-understood boundaries between legitimate users and nonusers are present" and (2) "Resource boundaries: clear boundaries that separate a specific common-pool resource from a larger social-ecological system are present" (Cox et.al, 2010). In order to enable management of each specific part of a CPR and thereby secure access for legitimate users, the first step is to define the entire connected system boundary, the boundaries for each sub-component of the system, and then assign responsibilities for management of each sub-component and each of its hierarchal layers.

Once clear boundaries are established, a water-sharing framework can be defined for the management of sub-system interactions under different conditions and for different periods. In this case, while physical and administrative boundaries are generally clear, in the Southeast Sulawesi Province definition of access rights and priorities as required under national law are generally unavailable. Such water-sharing frameworks typically clarify the total amount of water that is allocable to water users and the timing of when allocation announcements can be made (Davis, 2007; Young, 2014). Importantly, a robust sharing framework provides security to water users, including environmental uses, alongside use conditions and rules that allow water users to plan long-term production/conservation activities and day to day use. Further, these frameworks detail how access to water will be shared equitably under periods of short-term scarcity, such as during a drought. Thus, we find that, while DP criteria are generally well represented across institutions, the definition of allocation priorities needs to be clarified in system-wide plans and enabled through the National Water Law, so that the options available to local level managers are clear. Another important issue is the separation of local and system-wide flood risk management (FRM) rules. According to Henstra et al. (2019), shared responsibility among stakeholders, including the property owner, is central to any FRM regime. This signals the importance of spreading risk reduction costs over a wide spectrum of stakeholders to create individual or group incentives to independently mitigate flood risk and prepare for post-flood recovery (Henstra et al., 2019). Henstra, however, is silent on how to assign risk management responsibilities through a hierarchy. Currently, FRM in the study area is focused on the coordination of government agencies to address effects with infrastructure, with minimal, if any, participation by users exposed to flood risk. The tone is one that expects top-down direction and assigns minimal, or possibly even no, responsibility to local managers.

4.5.2 DP2A: Congruence with local social and environmental conditions

DP2A requires that: Appropriation and provision rules are congruent with local and system-wide social and environmental conditions as they change. Here, we use a slightly modified version of Ostrom's original DP, as suggested by Ma'mun et al. (2019a), which captures the capacity of institutional arrangements to adapt to change. In particular, institutional arrangements that can be expected to maintain congruence over time signify an ability to respond to scaled effects on CPRs as conditions alter (Bohensky & Lynam, 2005). Congruence with local social and ecological conditions is perhaps the most challenging issue in any natural resource management context.

Our analysis of the information collected from respondents found little evidence of local system-congruency. Only the Konaweha River in WS Lasoko-Konaweha has an annual water allocation plan. This plan involves five users: two state-owned water companies (PDAM) who supply water to Unaaha (the capital of the Konawe Regency) and Kendari City (the capital of the province), and three IDs under Central Government management. Importantly, the plan does not consider water demands from the downstream power plant located in the Konawe industrial zone. Furthermore, other IDs managed by Provincial and regency WRM agencies within tributaries that flow to the main river have been omitted from the plan, and none of these users have been formally registered. As a result, even at the sub-system level, the total limit on water abstractions and the duration of water licenses have not been formally defined. Figure 4 displays current water use, not limits to abstraction. For each ID, water abstraction is estimated only for the district as a whole, using rice area equivalents. All (rice) farmers are eligible users, and water "sufficiency" is the abstraction limit. However, "sufficiency" is understood differently by different farmers; thus, compliance is difficult to measure. Further, the total area of rice equivalent is not defined in a way that enables water rights to be adjusted in a fair and equitable manner as scarcity increases. That is, no formal priority-sharing system is in place.

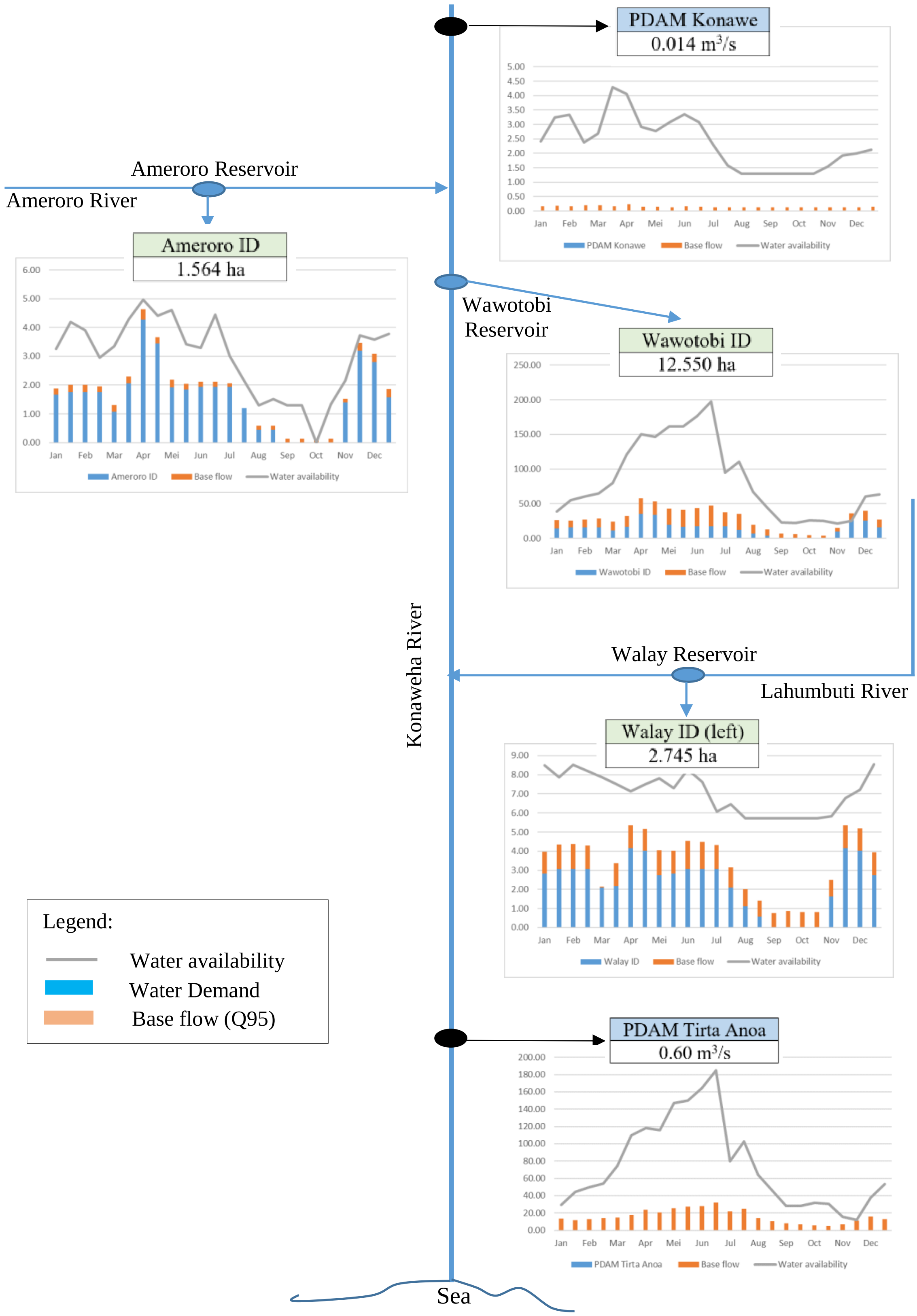

Figure 15. Dry year scenario (Q80) of annual water allocation plan in Konaweha River in 2018/2019

(Source: BWS Sulawesi IV, 2019)

Figure 15 suggests that, most of the time, water supplies are sufficient to satisfy demand; thus, scarcity reallocation rules are not yet a pressing issue. However, this is not true for smaller river tributaries, where IDs are exposed to significant seasonal flow variability and operate under different management arrangements (Province and regency) in the interconnected system. The wide use of continuous-gravitation flow methods also means that IDs and farmers do not equally share the risk of shortage during dry years. In these areas, the standard sharing mechanism applied during shortages is water rotation within the ID. Our interviews, however, revealed that the absence of scaled and equitable institutional arrangements to deal with scarcity events tends to increase the potential for rent-seeking behaviour to emerge between private agents and decision-makers at higher levels, at the cost of smallholder farmers, especially in WS Poleang-Roraya (Ma'mun, et al, 2019b). Without a clear water-sharing framework, efficient and equitable adjustment is difficult to achieve and is a clear threat to robust outcomes.

4.5.3 DP2B: Congruence between benefit and cost

DP2B requires that: Appropriation rules are congruent with provision rules [and] the distribution of costs is proportional to the distribution of benefits (Cox et.al, 2010). When the nested enterprises principle is put first, two essential questions emerge: (1) whether DP2B should apply to each level of the institutional hierarchy and (2) whether the determination of budgets is more efficiently decided centrally by a system-wide manager, at the ID level, or at both levels. As summarized in Table 14, budgets for water resource and irrigation development are determined at each level in the hierarchy; no single ID has its own budget or any authority to expend money on maintenance. Further, only BWS Sulawesi IV and the WUAs have the authority to set and collect fees from their users. However, although the DP implies a cost recovery objective, where proportional benefits are expected to be gained by users, compliance is typcially very low. When smallholder farmers with limited financial capacity to contribute beyond in-kind methods are unable to cover the cost for operation and maintenance, the current response is to search for and secure a government subsidy to ensure that system costs are met. Centrally provided and determined subsidies mean that infrastructure rehabilitation or replacement may be delayed because of budget constraints and distance from the decision-makers, often resulting in reduced system viability and productivity and community intolerance of mismanagement.

Thus, achieving DP2B congruency requires that the short-term costs of maintenance be recovered by local farmers at a minimum, leaving long-term costs to be recovered by the local WUA or ID managers. Of 152 WUAs in Konawe District under BWS Sulawesi IV authority, however, only 37 WUAs have managed to collect an ISF. Moreover, even though licensed users (i.e., hydropower, state-owned water companies, industry, and commercial agriculture) have been required to pay water charges called *Biaya Jasa Pemanfaatan Sumber Daya Air*, since 2004 delays to their formal definition has meant that this revenue has yet to be collected.

4.5.4 DP3: Collective governance

DP3 states that: Most individuals affected by a resource regime are authorised to participate in making and modifying its rules. (Cox et.al, 2010). Congruence with this DP is possible across the different institutional levels, from the national Dirjen SDA which discusses and seeks consultation on regulatory frameworks for water resource development, through the Basin Council which coordinates consultative forums at the basin level, down to the Irrigation Commission at the regency level where individual WUA, farmer, and licensed-user views can be captured. Only the WS Lasolo-Konaweha, however, currently has a Basin Council in Southeast Sulawesi. In all of Sulawesi Province's other Basins, a basin management institution has yet to be established. Moreover and under current law, the capacity of Basin Council institutions to act as a consultative or system-wide administrative body has proved challenging. In practice, they appear to have no authority to make and/or enforce decisions. Further, there is no clear metric available to determine how to evaluate the performance of each level in the administrative hierarchy and/or by each group of stakeholders listed in the Basin Plan. Instead, Basin Plans are typically drafted and promulgated by BWS Sulawesi IV or the relevant WRM agency, and it is seen as the responsibility of the Basin Council to simply implement the plan without any commitment to enabling “collective governance” and with neither the power to enforce compliance with the plan or raise the money necessary to implement it.

There is, however, evidence of collective coordination among and across the IDs. Each ID must supply a collective cropping plan for the WUAs in its area which is passed onto the Irrigation Commission. These cropping schedules, and a corresponding water distribution plan, are then discussed by the Commission, legitimized by the *Bupati* (regent), and validated for all irrigation systems in the regency (including those managed by BWS Sulawesi IV or the province’s WRM). This process usually occurs at the beginning of the year, and each ID is then authorized to take water in accordance with that cropping plan with no further need to consider impacts on other IDs.

4.5.5 DP4A: Monitoring of users

DP4A states that: Monitors are accountable to the users with enforcement capacity for ensuring compliance with the appropriation and use rules (Ma’mun et.al, 2019a). Lack of monitoring appears to be significantly constraining the effective management of water resources in Southeast Sulawesi. Not all users are registered and enforcement of non-compliance with governance rules is weak. Monitoring and enforcement was originally regulated under the 2004 WRL and performed by a team of *Penyidik Pegawai Negeri Sipil*, or civil servant investigators, through BWS Sulawesi IV. With the annulment of the WRL in 2015, however, that legal authority and thus the capacity of the agency to enforce compliance at the basin level was weakened.

Although water users at ID level should be familiar with the importance of collective monitoring and enforcement, over the last two decades similar reductions in system compliance have also been noted. As discussed above, different interpretations of water "sufficiency" also make it difficult to hold WUAs and farmers in check. This issue was mentioned several times during the FGDs and interviews. While farmers at the top of an irrigation system will enjoy abundant water, conveyance losses from deteriorated infrastructure and excessive abstraction by other users typically mean that farmers at the tail-end of the system either receive less water or experience delays to their agreed schedule. As a result, downstream farmers bear most of the risk of waterlogging (poor infrastructure) and non-delivery during variations in climatic conditions (e.g., flood or drought).

In a typical hierarchical institutional arrangement, each level would be accountable to their stakeholders and have the authority to enforce compliance at the next level down, but not be responsible for levels two or more removed from their own (Simon, 1962). With respect to this DP, we find that attention to user enforcement is needed, particularly at the system-wide level. To do this, arguably the first step is to require each level in the hierarchy to document all use entitlements and assemble them into a framework so that effective monitoring and enforcement at each level is established.

4.5.6 DP4B: Monitoring of resource system

DP4B requires that: System-wide monitoring and reporting exists and is reported to users (Ma'mun et al., 2019a). In Southeast Suluwesi, regular monitoring of water resource conditions exists at the river basin level. The Basin Council coordinates with other sectors—such as the Meteorology and Geophysics Institute and Department of Energy and Mineral Resources, who are responsible for groundwater—to turn the data collected into a coherent description of aggregate water use at the basin level. This progressive coordination has not previously been achieved. Annual reporting of hydrological conditions is now available and can be accessed through the BWS Sulawesi IV website. These data are also used to develop annual water allocation plans, and for the IDs to schedule water distribution at the beginning of a cropping season. While available, typically, this hydrologic information is not yet being used optimally to inform users about the risk of drought or flood in a timely manner. Furthermore, coordination of monitoring and enforcement of water abstraction activities has not been fully integrated in many basins. Although some of these activities require technical guidance from the river basin authority, as discussed above rule enforcement is lacking. As a result, according to FGD and workshop participants, deterioration of water resources, accumulation of sediment yield in rivers and irrigation canals, and declining water quality is being tolerated. It needs to be acknowledged, however, that while the system-wide monitoring necessary to include facilitate robust water accounting is nonexistent, the data which is available is being used to guide water allocation planning in Konaweha River (Figure 15).

4.5.7 DP5: Graduated sanction

DP5 states that: Sanctions for rule violations start very low, but become stronger if a user repeatedly violates a rule (Cox et.al, 2010). The 2004 WRL set clear penalties for infringements of water use rights by water-affecting activities, which have persisted and been updated in WRL No. 17 (2019, article 68–74). Similarly, Government Regulation No. 68 (2014) details graduated or tiered administrative sanctions progressing from three written warnings to the temporary suspension of a water license and finally the revocation of a water permit for repeated offences. Given this experience, it seems reasonable to assume that regulations under the new WRL will be similar. At present, the Ministry of Public Works Regulation Act (2015) is being used as an interim regulatory mechanism; however, it is less detailed than that of government regulations, so lower sanctions currently apply for non-compliance.

At the river basin level, however, Basin Plan operational polices are general in their description of sanctions and, generally, fail to establish the processes necessary to apply sanctions. Thus, at present, the majority of rule violations go unpunished. The FGD and interviews also revealed that the same issues are present at the ID level. At best, ID sanctions extend to informal sanctions, such as user shaming or reproach by irrigation staff. Thus, we conclude that there is considerable scope to improve sanction processes at all institutional levels.

4.5.8 DP6: Conflict resolution mechanism

DP6 requires that: Rapid, low-cost local arenas exist for resolving conflicts among users or with officials (Cox et.al, 2010). Conflict resolution mechanisms between WUA members and among WUAs in an ID are aligned with what Ostrom (1990) described as rapid and low cost. At the local level, the use of customary Indonesian practices that consider the musyawarah (a forum for discussion and negotiation to reach mutual consensus) are a preferred way to settle disputes. Importantly, the WRL allows the use of this customary practice to resolve conflict before escalating to formal adjudication in the courts. As such, musyawarah practices at the lowest institutional levels are legally binding. In support of this, BWS Sulawesi IV, the WRM agencies, and an Ombudsman provide channels for mediation between conflicting parties. FGDs, however, revealed that this mechanism is not always effective when dealing with national or multinational companies operating in the area. This situation links to Design Principle 4A and 5 and may, in part, to be associated with a lack of system-wide monitoring and failure on the part of the WS Poleang-Roraya authority and related government agencies who issued the permit. The result is an arrangement where there is opportunity for mis-compliance with system obligations as companies are not held accountable for the external effects of their activities. For example, conflict between local farmers and a nickel mine in the Tinanggea sub-district of Konawe Selatan (part of WS Poleang-Roraya) had not been resolved at the time of this study, despite several years of farmer efforts to seek justice through formal and informal channels including assistance from field irrigation staff in the area (Ma'mun et al., 2019b, under review). As such, we conclude that there is scope for the improvement of conflict resolution arrangements at all levels in the institutional hierarchy.

4.5.9 DP7: Minimum rights to organize

DP7 requires that: The rights of local users to make their own rules are recognised by the government (Cox et.al, 2010). Water resource management in the study area is largely the responsibility of central and provincial authorities. Both have the mandate to administer, organize, and manage water resource development in their respective river basins. Likewise, separate authorities exist for each defined irrigation districts as outlined in Figure 3. Typically, each management structure includes staff from BWS Sulawesi IV, the provincial WRM, or the regency's WRM. Also, the regency's WRM can ask BWS Sulawesi IV or the provincial WRM to replace any staff who is experiencing or causing problems with water users or failing to properly coordinate with WRM requirements. Meanwhile, the Central Government can appropriate infrastructure from a regency's WRM if they lack capacity to deliver the required outcomes. More generally, At the local level, WUAs have the right to create and implement their own rules and WUAs are encouraged to organize into unions and federations at secondary and primary canal levels, respectively. This enables WUAs to be represented in decision-making processes at higher ID or province levels.

4.6 Discussion

4.6.1 Insights from the dimensions of TCE and nature-related transactions

Water governance in Southeast Sulawesi is currently transitioning to a new set of institutional arrangements. In particular, as the regulations necessary to implement the 2019 WRL are applied, there is considerable opportunity for improvement. In an attempt to inform this transition we have trialled, and herein applied, a revised ordering of Ostrom's DPs to search for gaps and mismatches. The approach we have taken is in line with prior suggestions by Simon (1962, 2001). Under the current regime, appropriate balancing of social and economic objectives while maintaining sustainable use appears challenging. Before offering a summary of possible alternative governance structures that arise from this assessment, the nature of this challenge is examined through a transaction cost framework and the dimensions of nature-related transactions to explore how the current institutional structure fails to mitigate *ex-post* implementation hazards.

Four transaction dimensions are used to evaluate current structure alignment: asset specificity, uncertainty, frequency, and complexity/interconnectedness. TCE suggests that asset specificity, uncertainty, and frequency are needed to assess transactions (e.g., reallocation outcomes) and the governance structures that support transactions (Williamson, 1985). *Asset specificity* exists where the bilateral dependency on an asset (e.g., water resources) is high, and resources cannot be instantaneously transferred to the best alternative use. Asset specificity assumes greater importance in the presence of *uncertainty*, where conflict and dispute drive the emergence of non-standard contracting arrangements. Under such scenarios, assessment of governance structures is highly warranted. High transaction *frequency* allows the cost of specialized governance investments to be recovered, whereas low transaction frequency incentivizes high costs to settle disputes and continued uncertainty. Finally, the extent of *complexity and interconnectedness* determine the extent to which the users of a system are affected by the choices of others, and the extent to which problems may need to be decomposed into smaller units of analysis to cope. Ideal institutions will facilitate such processes as motives for transacting to adapt, reallocate, and meet shared objectives (Hagedorn, 2008). For the case study area, we observed the following transaction dimension outcomes.

Asset specificity

We observed that reallocation between water users—all with asset-specific requirements to a range of production systems (e.g., agricultural, urban consumption, power generation, and industrial uses)—will be challenging in the case study sites during times of water scarcity. Institutional arrangements that allow trade-offs between users have not been built into the system; thus, either capital losses or increased illegal activity (e.g., water theft) can be expected to occur. Different users will experience different losses depending upon the scale and scope of asset specificity effects. As such, there is an opportunity to amend Basin Plan governance arrangements so that these issues can be taken into account. To do this, effective sharing and priority management rules could be added to the Basin Plan so that such arrangements can be applied when needed.

Uncertainty

Uncertainty can take many different forms. The effect of a random act of nature on the water sector is unpredictable. As discussed, any lack of clarity about how managers will respond to water scarcity creates uncertainty for users. Similarly, where user compliance with contracts or sets of rules is uncertain for other users, transaction costs tend to rise (Coggan et al., 2010). Our interviews also suggest that many stakeholders still consider Southeast Sulawesi to be characterized by water abundance and, hence, consider little need to worry about supply or demand uncertainty. However, we contend that, while the governance system may appear capable of dealing with seasonal or incremental change, the current system would struggle to cope with a rapid change in supply and demand. The cost of introducing priority sharing arrangements before they are needed is low; however, once they are needed, the cost will be high. In particular, the literature suggests that there are opportunities to increase both the security and flexibility of the current system (Livingston, 1995; Quiggin, 1988). Sharing arrangements are also missing in the Basin Plan, as already discussed. The highly attenuated property rights regime has led to the issues of credible commitment and security of expectation

(Williamson, 1985), which also undermine existing institutions and future reliance upon them by users.

Frequency

At each management level, water allocation is a recurring transaction. Questions that must be considered in this context include how often transactions occur, how many users are involved, and whether users or types of water right holders are treated equally or whether defined priority management rules would improve use. Designing appropriate institutional arrangements to deal with frequency issues can be predicted to reduce the cost of collecting information and, also, negotiation between users. System changes should seek to increase the frequency of reallocation and reduce transaction costs (Coggan et al., 2010), and build trust among users, agents and authority at all levels. Further, it can be predicted that increases in transaction frequency will reduce uncertainty and opportunistic behaviour (Rørstad et al., 2007) and overcome the existing sense of distrust which, among other things, has caused declines in farmer willingness to contribute to maintenance and generally contribute to management in a constructive manner.

Complexity and interconnectedness

Water management is complex, as its flows and losses often make sequential or re-use possible (Hanemann, 2006). In particular, Basin Plans could be rewritten so as to acknowledge the fact that many groundwater systems contribute water to surface water systems and vice versa. As a general rule, interconnectivity needs to be acknowledged before it can be managed.

Variability of supply in time and space adds to this complexity and requires coordination at the system-wide level. Further, system interconnectivity means that externalities resulting from water-affecting activities also need to be considered. Whether this complexity is most effectively managed at the basin level or devolved via manageable tasks to a sub-system or ID level warrants consideration. Not all rivers or sub-catchments in river basins have the same conditions or face the same problems and challenges. Limitations to human cognition and high transaction costs for collecting information suggest that detailed decision-making is most efficiently left to the lowest level of governance, where people are more familiar with the local context (Garrick, 2015; Hayek, 1945; Marshall, 2008) and special arrangements can be implemented to facilitate trade-offs between or among sub-systems.

The assessment across these four transaction dimensions suggests a low level of alignment between current institutions and (future) reallocation objectives/requirements, in turn suggesting poor design and implementation with respect to Ostrom's DPs. The following section discusses the implications of this situation and the case for the development of alternative governance structures.

4.6.2 Options and opportunities

The above attributes help to identify the nature of institutional changes that would bring increase alignment with Ostrom's DPs and, more importantly, with Central, Provincial and local objectives. Ostrom design principles were developed in an effort to assist, not as an objective in themselves. The rigidity of the current system means that it is incapable of accommodating changes in supply and demand without a major restructure, which, if required as a result of a crisis, could prove extremely expensive. This has two consequences that have been noted elsewhere in Indonesia. In particular, the current system can be predicted to: (1) create conflict between sectors or users and (2) in the future, encourage more (unsustainable) groundwater abstraction. Without appropriate regulation, monitoring, and enforcement, this will ultimately lead to environmental and salinity problems, as already reported in Bali (Cole & Browne, 2015). As Srinivasan et al. (2012) have observed such institutional design flaws are one of the root causes of the unsustainability and sectoral vulnerability that tends to drive the emergence of water crises.

If efficient and equitable forms of development are to be encouraged, then mechanisms that enable inter-sectoral and inter-regional adjustment are necessary. While administrative reallocation may be justified, it is prone to rent-seeking behaviour at the expense of violating the principle of equity and fairness (Livingston, 1995). Without actual compensation through voluntary transfers of existing user rights to others, traditional users (smallholder farmers) tend to be marginalized.

To safeguard priority uses and balance socio-economic objectives, as stated in the Water Law, it can be reasoned that the regulations, subsequent Basin Plans and associated institutional arrangements must be crafted to maintain order, mitigate conflict, and foster mutual gains among competing uses and users (Williamson, 2000). One of the options identified in this paper is the development of sharing arrangements that enable the development of nested adjustment mechanisms at both the sub-basin and local level. These would benefit further from their coupling with arrangements that limit total withdrawals from the system as a whole, for each sub-system and most diversion points, and the introduction of prioritized proportional adjustment rules when the full share entitlement cannot be met (Young, 2019).

For example, if a state-owned company locates downstream (Figure 15), requiring more water to supply Kendari City, then one or more IDs or WUAs in the system will need to forgo some of their use rights. In consideration, the Basin Plan and proposed regulations could require the city to provide compensation equal to the value of loss imposed on the ID, WUA, and/or individual farmers. Such a rule would do much to reduce uncertainty and provide the security and legitimacy necessary to bring trust and respect back to the entire system and each hierarchical layer, as it is only when water use rights are secured and protected that stakeholders can be expected to be willing to invest to maintain the actions necessary to ensure the productive use of the water resources on which they currently depend (Randall, 1983).

Changing the subsidiarity status of local IDs is another possible governance option. Subsidiarity arrangements are designed to prevent system-wide managers from interfering with local management decisions so that they can be made in a timely manner. They operate by limiting the extent by which system-wide managers can interfere. They can, for example, determine broad sharing rules and sub-system exchange rates but not where and what water is used for. Granting more authority to IDs would allow more efficient use of local knowledge about users, and opportunities for users to interact with one another and the wider economy. This would, for example, enable the local development of institutional rules that enable the immediate reallocation of water, rather than waiting for system-wide responses to be negotiated and implemented (Ostrom, 1999). Moreover, since WUAs already have legal status, unions or federations of WUAs could act as monitors of IDs' performance. This arrangement would make IDs more accountable to the WUAs/farmers they serve and increase the likelihood that WUAs/farmers would be fairly treated and could exercise their access rights, as specified by the Water Law. At the same time, IDs could hold WUAs accountable for rule compliance, as under such a system each ID would be required to conform with system-wide regulations. The BWS Sulawesi IV and/or the WRM agencies would then only need to ensure that system-wide monitoring, enforcement, graduated sanctions and easy access to conflict resolution mechanisms are in place and are being used.

4.7 Conclusions

Indonesian water governance is entering another era and as it does so an opportunity to address hierarchical arrangements has emerged. The WRL in 2019 is designed to balance social, economic, and environmental needs while safeguarding public rights to access water and ensuring that water is used for the greatest benefit of the people. The WRL also requires the development of allocation priorities. Current water governance structures in Southeast

Sulawesi Province, however, appear to be hindering progress towards high-order social and economic objectives, as well as the development of a capacity to cope with efficiently manage predictable future changes to water supply and demand.

Using a revised ordering of Ostrom's DPs with a focus on hierarchical institution design arrangements, and the use of TCE, we have examined institutional arrangements for several river basins in Southeast Sulawesi. In particular, we sought to assess how this perspective can be used to help inform efforts to improve institutional arrangements. In systems where hierarchical structures are necessary, we conclude that additional emphasis on boundary definition enables efficient development of the institutional arrangements necessary to improve outcomes. In particular, it forces the development of inter-sectoral and inter-regional allocation and reallocation rules and, through this, enables the development of more sustainable outcomes.

Moreover, our analysis suggests that an initial focus on boundary definitions is an essential starting point for the development of Basin Plans that are characterized by security in a manner that does not compromise system capacity to facilitate and even encourage regional development. In practice, we have concluded that a revised ordering of Ostrom's DPs helps draw attention to this significant institutional design opportunity. By considering Ostrom's "nested enterprises" first, rather than last, in her list of principles, it becomes much easier to apply all the other principles in her list—especially when large-scale CPRs and a multitude of governments are involved. This concept is currently lacking in the literature.

When she published her work, Ostrom (1990) asserted the importance of the nested enterprises principle when a CPR is part of a large, complex system. We concur with her argument, as have Evans et al. (2014) and Lacroix and Richards (2015). However, whenever and wherever interconnected and complex systems are under investigation, we conclude that earlier rather than later attention to this principle will produce significant benefits. When the nested enterprises principle is placed first in her list, an important hierarchical perspective is added to all her remaining DPs.

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Chapter 5: Summary, conclusions and policy recommendations

5.1. Introduction

Indonesia has long been known as an agrarian country. The history of irrigated agriculture dates back to the fifth century in Java and Bali. Its remains can still be seen in the *Subak* system in Bali, one of the UNESCO's World Heritage cultural landscapes. Nevertheless, the future of irrigated agriculture in Indonesia, including the sophisticated Subak system, is challenged by uncertainty in the ever-changing environment. To address these challenges, a series of policy reforms in the water and irrigation sectors began in 1999. They started with the renewal of the Irrigation Management Transfer (IMT) policy, as part of the Water Sector Adjustment Loan (WATSAL), funded by the World Bank. The results, however, did not meet expectations (Oad, 2001; Suhardiman, 2013). Many of the reforms were therefore abandoned. Against this background, this study sought to find answers to the research questions:

1. Are there plausible water management options that could maintain Indonesian agricultural systems and rural economies, without constraining water availability for the development of other sectors?
2. What set of institutional arrangements would enable the most efficient and equitable use of water in Indonesia?

Using the above questions to guide the research agenda, this thesis used the Common-Pool Resources (CPRs) theory, specifically the eight design principles (DPs) for robust institutions, proposed by Elinor Ostrom in 1990. The research had three objectives:

1. To investigate necessary and sufficient conditions for institutional arrangements that promote robust irrigation systems.

2. To investigate whether institutional arrangements at the local level are capable of dealing with future uncertainty and changes in water availability.
3. To search for possible alternative institutional arrangements to govern water resource development in Indonesia, and the processes needed to create the capacity of the governance systems to properly manage water.

The first objective was discussed in **Chapter 2**. It outlined lessons learned from long-enduring, community-based irrigation systems around the world. The results produced the insights necessary to consider the second objective, addressed in **Chapter 3**, by employing an adapted set of principles to a case study of local irrigation systems in Indonesia. The findings in **Chapter 3** were then used to inform **Chapter 4's** investigation at the system-wide level**,** thus addressing the third objective.

The remainder of this chapter provides a summary of the main findings, including the contributions to methodology and CPR theory in this thesis and, also, policy recommendations. Finally, the last section discusses the limitations of the study and outlines suggestions for further water and CPR research.

5.2. Summary of main findings

Studies on CPR management have been criticized for their lack of analytical rigour (Agrawal 2001). Moreover, there have been few attempts to determine the relationship between specific DPs and the outcomes that CPR management institutions are expected to deliver. The research presented in **Chapter 2** aimed to fill this gap through the examination of sixty-two irrigation case-studies located within thirty-seven countries.

Using fuzzy-set Qualitative Comparative Analysis (fs/QCA), **Chapter 2** explored the question of whether Ostrom's DPs represent a complete set of necessary conditions or, better still, a set of conditions sufficient for the development of robust institutions. Because it can handle fine-grain causal complexity, fsQCA offers an effective methodology. I find that fs/QCA is especially useful in unpacking relationships among the equifinal, substitution and complementary effects of institutional arrangements and the overall effectiveness of an institution.

Out of the eight principles, the study identifies four principles that can be described as necessary conditions for a robust water institution; these are: 1) Clearly defined boundaries, 2) Monitoring of users, with enforcement capacity, 3) System-wide monitoring of resources, and 4) Minimum rights to organize. Ostrom's other principles are useful but were not found to be necessary. The result also shows two parsimonious solutions (minimum or core configuration of conditions) that are sufficient for robust institutions.

The first solution involves *user monitoring* AND *system-wide monitoring*. That is, the productive use of water resources and irrigation systems can be sustained when the monitoring of user behaviour entails enforcement capacity, helps to ensure compliance and prevent opportunistic behaviour and is organized so as to provide timely information necessary to allow adjustment of rules for maintenance and appropriation.

The combination of *congruence with local condition* AND *system-wide monitoring* AND *minimum rights to organize* is the second parsimonious solution. That is, when users have the authority to self-organize and devise their operational rules within a defined framework, they can adapt to changes in various conditions, providing that they have access to timely information about the state of their resources.

As a result of this analysis, a water-specific version of Ostrom's design principles was developed.

The modified version of Ostrom's DPs was applied in **Chapter 3.** This chapter examined the robustness of Water User's Associations in Southeast Sulawesi Province in

Indonesia. The research collected data from a series of interviews, a stakeholder workshop and six focus group discussions in three of the province's regions. The study resulted in recommendations to improve irrigation management institutions in Southeast Sulawesi and Indonesia, generally; summarised in Table 5.1. The recommendations are presented as a list of propositions worthy of consideration by Indonesian water managers.

Table 5.1. Propositions for sustainable irrigation institutions in Southeast Sulawesi

Proposition 1	System robustness can be improved by formally defining a limit on water withdrawal for individual farmers, either by area or volume, and clear criteria for priority allocations if/when scarcity occurs.
Proposition 2	All farmers in WUA-managed areas need to be registered and their records need to be kept and updated by the WUA. Records may include total area, number of plots, location, and type of crops (in different seasons), and rules for water sharing during periods of supply scarcity.
Proposition 3	Providing choices for irrigation service fee (ISF) payments through service or monetary obligations, or a combination of both may increase farmer contributions to irrigation operation and maintenance (O&M).
Proposition 4	At WUA level, enforcement capacity and monitoring needs to be improved. Although farmer decisions to hold water at the head-end of irrigation system may not affect neighbouring farmers in water-abundant areas, such decisions may be harmful to tail-end users as discussed in the DP 2a section. Affected users must be able to rely on effective monitoring and compliance mechanisms.
Proposition 5	Formal, graduated sanctions that define penalties for low to severe infringements will be useful for preventing rule violations, particularly where those sanctions, or penalties, are transparent and apply to all users.
Proposition 6	Informal conflict resolution mechanisms exist locally. What is urgently needed is a mechanism enabling local institutions to engage in conflict resolution at higher management levels.
Proposition 7	Individual gains at the expense of others in a system can be avoided by giving WUA/farmers' groups more authority (rights) to decide what they want to do within their irrigation system, and how they want it to be developed—as long as it does not contradict the system-wide rules or responsibilities.
Proposition 8	In the absence of system-wide rules, WUAs need to strengthen the horizontal linkages between them, to share water more equitably and increase their bargaining position when facing current/expected impacts of other user activities that are directly/indirectly relevant to the irrigation system.

As **Chapter 3** developed, it became clear that putting the nested principle last in Ostrom's list of eight principles tends to encourage insufficient consideration to its relationship with the other seven principles. That is, this ordering of the principles tends to focus attention on local issues and discourage consideration of hierarchical issues. **Chapter 4** focused on the development of guidelines for the nesting of local management arrangements within broader hierarchical arrangements.

Chapter 4 begins by putting Ostrom's nested principle and considering it first in the examination of the robustness of the institutional arrangements used to manage a complex, large-scale CPR system, with heterogeneous values and uses. Many studies of large-scale CPR systems, using Ostrom's DPs, show mixed results; that is, not all principles are relevant to large-scale CPRs. As this work progressed, it was found that the order in which principles are considered matters. By putting the nested principle first, a new perspective emerges – all principles remain relevant. Specifically, the user of Ostrom's DPs is forced to consider how to interpret and apply them throughout the hierarchy in the way Ostrom acknowledges is necessary.

To test this argument, in **Chapter 4** the approach is tested through an examination of river basin management arrangements in the province of Southeast Sulawesi. The chapter makes use of Chapter 4's data, in addition to a review of regulations, existing basin plan documents and relevant studies conducted during the period of the promulgation of the first water law. That is, Ostrom's DPs are combined with a transaction cost analysis.

In the basin examined, the results show that institutional arrangements do not provide the flexibility necessary to enable users to adapt to foreseeable future changes in an efficient and equitable manner. This is important. As suggested in the literature, hierarchical arrangements matter in determining the robustness of a water allocation system (Challen, 2000;

Simon, 1962). Further, the analysis also found that the hierarchical structures of the extant institutions do not align with the complex nature of water resources in the province. The results provide a list of gaps in the institutional arrangements that need to be addressed and changed so that water use can be kept within sustainable limits as communities pursue a range of economic and social development objectives.

5.3 Methodological insight: A fuzzy-set Qualitative Comparative Analysis

Qualitative comparative analysis (QCA) is a relatively new methodology, developed by Charles Ragin in 1987. The use of the methodology has increased in the last three decades and has become one of the mainstream approaches in sociology, political science and health service research (de Block and Vis, 2018). Recently, the methodology has also been used in the environmental and water sectors (see, for example, Hamidov et al., 2015; Knieper and Pahl-Wostl, 2016; Pahl-Wostl and Knieper, 2014; Srinivasan et al., 2012). Nevertheless, these developments have yet to achieve a standardized method, especially in the use of fuzzy-set calibration techniques necessary to enable analysis. My search of the literature revealed that, to date, only Basurto and Speer (2012) and Toth et al. (2017) have proposed a specific fuzzy-set calibration technique. These techniques they have developed are valuable but remain subjective in helping research assemble the final fuzzy-set scores necessary to enable analysis (de Block and Vis, 2018). Moreover, as we proceeded, we found that their techniques not to be suitable for analysis of the meta-data used in this study.

The method used in this research offers an alternative technique, which can be applied to qualitative concepts/data in general and helps to reduce arbitrariness in the development of fuzzy scores. The methods section in **Chapter 2** provides a clear and replicable iterative procedure for qualitative data calibration. The technique emphasizes the importance of developing meaningful concepts and corresponding scores to capture the ideas within each concept, both in causal conditions and in outcomes. The Analytic Hierarchy Process used to score the fuzzy-set, as an important part of the calibration procedure. The score is developed by assigning suitable criteria to each concept from a careful assessment of best practice examples and insights gleaned from the established literature. Then, a two-step, pair-wise ranking process is used to weight each criterion and assign scores that can be applied to each case and used for the analysis.

5.4 Revisiting Ostrom's Design Principles for robust institutions: a water focus.

In all the analytical chapters, Ostrom's DPs were used as diagnostic tools to organize information and search for insights and practical ways to improve existing arrangements. In doing so, following Ostrom's (2005, 2008) suggestions, each DP was turned into a question: *what further arrangements does each design principle need to improve the robustness of the institution in governing common-pool resources (CPR)*? This approach proved to be powerful. It replaces the search for the presence or absence of a design principle with a search for gaps between institutional arrangements prescribed by a DP and the reality, and it then goes on to identify measures that can be taken to address these gaps.

With an extensive review of the literature and the assumption of *bounded rationality*, I developed the fuzzy concepts of the DPs to evaluate the irrigation institutions discussed in **Chapter 2**. The same approach was used in **Chapter 3** to develop a checklist for use in **Chapter 4**. Findings from these chapters provide the basis for the policy recommendations made in this chapter.

5.4.1. Modifying Ostrom's design principles: putting the nested principle first

Ostrom's original "nested enterprise" principle stated that:

> *"When a common-pool resource is closely connected to a larger social-ecological system, governance activities are organized in multiple nested layers"* (Ostrom, 2010 p. 653)

Arguably, the most important insight offered in this thesis is the proposition that, when considering the robustness of any set of institutional arrangements being used to manage a CPR, Ostrom's nested principle should be considered first, rather than last. As Berkes (2006) suggests, rather than focusing on the scaling-up problem, it is more meaningful to understand the nature and dynamics of the cross-scale linkages when dealing with multi-level CPRs. Putting the nested principle first forces such analysis. In particular, it forces application of the principles within a well-defined institutional structure (Bromley, 1985) and, where appropriate, forces careful consideration of the case for ensuring that they are implemented at one, or more, levels in the hierarchy. Bromley (1985) discuss how institutional arrangements can fit together when the legal frameworks, which are defined at the policy level, are refined and further specified at the organizational level in a manner that creates codes of conduct and drives the behaviour of individual maximizing agents, as they go about their daily activities.

The importance of a hierarchic perspective in examining complex systems was discussed much earlier by Simon (1962). In essence, well-designed hierarchical structures assign tasks to levels in ways that decrease transaction costs by reducing the need for continuous consultation between levels in the hierarchy and reducing the need to have all decisions taken at a lower level approved by a higher level (Simon 2001).

The nested concept creates an expectation that the higher-level system rules take precedence over the lower-level rules. However, if lower-level rules are organized so that they conform with constraints imposed from levels higher in the system, this arrangement need not result in higher transaction costs. That is, the nested framework chosen needs to be designed so that there is no overlap in the nesting and full accounting of the interactions between the nests is possible. When such an arrangement is in place everybody knows who is responsible for what and who is accountable for what. The other seven design principles can then be applied to those levels where they are likely to be most effective but careful account must be taken of the consequences of implementing them at one level on the processes managed at another level in the hierarchy.

5.4.2 Where to from here

Institution is complex and multidimensional. It is dynamic and evolves overtime. Institutional arrangements are shaped by human interaction, and interplay of various aspects, including social, economy, political and environmental aspects (Cleaver and de Koning, 2015). This raised critique that Ostrom's DPs are too simplistic and overlook the complex nature of the CPR and the community where the principles must be applied (Stenins and Edward, 1999; Cleaver and Franks, 2005). While admitting this limitation, Ostrom's empahasized the importance of understanding how the configuration of the design principles as causal conditions affect incentives, behaviour and outcomes (Ostrom, 2008). My analysis in **Chapter 2** support her argument. Further, unpacking the design princples within each layer of the nested arrangement is useful to examine the complex nature of human interaction in a particular CPR setting, as demonstrated in this study.

Although the reordering of the design principles is based on analysis of the water sector, Ostrom's design principle is written in general terms and can thus accommodate other types of CPR. I believe the lack of specificity of the design principles (Ostrom and Cox, 2010) fits wider purposes and so can be applied to all types of CPRs. However, when applying the design principles for analyzing CPR institutions, it is more fruitful to identify the design elements of each of the principles that best fits with the characteristics of the CPR under study, as well as the characteristics and objectives of human interaction with the CPR (Bromley, 1992). **Chapter 4** provides an example of the design checklist in the water sector.

5.5 Policy recommendations

5.5.1 The issue

In the search for a robust method to deal with Indonesia's significant water supply and demand management problems, there have been two recent attempts to reform water law. In both cases, in 2004 and 2019, the reform process, its framework and its strategy are incomplete. In particular, they fail to deal with the reality that, in an increasing number of regions, water is no longer abundant. Current supplies are no longer keeping up with demands and curtailment of supply is becoming increasingly common. As a result, conflict among users and competition between users is becoming more common and is expected to rise, even in areas where supply enhancement is still possible. Focusing investment on supply is not a long-term solution – supply enhancement can buy time, but it rarely produces a solution that can be expected to endure. Ultimately, an efficient way to manage scarcity must be found. Moreover, Damania et al. (2017) warn of the paradox of increasing water supply. Increased demand once accommodated creates its own demand and this leads to increased vulnerability to future droughts. Because of this, this thesis searches for a suite of institutional arrangements that can be relied upon to ensure that the Nation's water resources are well managed and, hence, are not a barrier to social and economic progress.

Based on the findings of this thesis, two key observations warrant further consideration in policy development. First, under the current water allocation regime, keeping use within sustainable limits, while allowing social and economic progress, is becoming increasingly challenging. In such a situation, the arrangements used to govern water use can impede progress. The water law of 2019 has contains a general guideline for water allocation that requires the development of priority sharing arrangements but appears to lack flexibility. At the system level, however, there is no clear framework to guide water allocation among districts, or regions, and no guidance on the most appropriate manner to manage shortages and changes in demand. Moreover, since there is no requirement to register all users and many users are not registered, it is impossible to regulate total abstraction and, hence, assure compliance with any regime that is developed. These are serious institutional short comings.

Second, the current law fails to provide guidance on the most appropriate hierarchical structure, or structures, and the processes necessary to support local governance arrangements. Our data, in **Chapter 3** and **Chapter 4**, shows that local farmers are extremely vulnerable to external pressures. That is, they are vulnerable to increased water extraction from parts of the system above them. Even when they can establish priority use rights within their system, there is no arrangement for them to protect their interests from development in other parts of the system. In particular, there is no way for them to protect themselves from increases in non-agricultural sector demands for water. This thesis' findings indicate that some of the problems faced by local communities have their origins outside their local boundaries. To enable their management, much more attention to hierarchical arrangements is needed. Communities need to be supported by higher-level elements of the system.

It is suggested that the way forward is to improve the management of hierarchical arrangements so that those responsible for allocating, managing and facilitating the use of water are able to ensure that water makes the greatest contribution to the full range of social, economic and environmental objectives while keeping its use within sustainable limits. It is time to search for a way to transition towards the adoption of water allocation systems that allow water to be shared fairly and equitably to meet changing circumstances.

Based on these findings, this thesis recommends that the basin authorities in Southeast Sulawesi (BWS IV Sulawesi and the Provincial Water Resource Management Agency), and policymakers in the Directorate General of Water Resources (DGWR), develop a water-sharing framework that can be used to guide the development of water basin allocation arrangements that reliably facilitate the management of two types of change. The first type of change to supply and demand involves a rapid event; for example, the emergence of a drought. The second type of change involves a slower, but more enduring, change in demand due to, for example, urban population growth or the construction of a new factory or mine.

5.5.2 High-level outcomes

The Water Law No. 17, enacted in 2019, envisages possible harmony in the pursuit of environmental, social and economic objectives affected by water use. The information presented in thesis suggests that the pathway to harmony lies with the development of hierarchical governance and allocation arrangements that enable local water users to become more involved in setting the rules and in determining the way that new demands are to be accommodated. That is, there is a need for an institution-wide set of rules that require, without compromise, the development of mechanisms that enable adjustment and re-allocation at the regional level but require that this be achieved in a manner that does not leave existing users worse off. For this to be achieved, much clearer rules about the sharing of water between connected water resources are necessary. Formally legislated water sharing rules and plans consistent with those rules are necessary.

5.5.2 Auditable outcomes

It is important that the high-level guidance, as set out above, is translated into operational concepts, or criteria, against which the Basin Authority performance can be measured and held to account by provincial and central governments and that the DGWR be responsible for ensuring that this happens. The role of water-sharing plans should be to guide each Basin Authority as it seeks to deliver the desired outcomes over a ten to twenty year period (according to the period of the Basin Plan, or *Pola*) and which can be revisited/updated every five years.

Based on this thesis' findings, and in addition to the propositions in Table 5.1, it is recommended that consideration be given to the suggestions made in the Box 5.1 below:

Box 5.1
Box 5.1 **1. Clearly defined boundaries of water pools (system-wide, sub-system or components) to be managed in a hierarchical structure, and rules for assigning water use rights from each pool that are clearly defined**. In Indonesia, this will require that: • The total amount of water available in the pools is known and water for system maintenance is set aside before water is issued to environmental and consumptive users. Entitlements should be defined as shares and allocations be made in proportion to water availability and in alignment with defined priorities; • Connectivity between water resource pools is understood and considered when making water allocations with careful attention to surface and groundwater connectivity and takes full account of downstream impacts; and • Ensures that an off-set rule is applied. That is, when the resource pool reaches its developmental limit, any new entry or proposal for expanded use by an existing user is permitted only when other users giving up their entitlement to the same amount. There are various terms mentioned in the Basin Plan (*Pola*), i.e. water district, catchment area, sub-catchment, and irrigation district. Any of them can be defined as a water pool to be managed as a subsidiary unit; the smaller unit is nested within the larger one in the hierarchy. While operating independently, the subsidiary unit should conform to the system-wide rules and plan. Advantages (Ostrom 1999; Simon 1962; 2000) These arrangements can be predicted to • reduce the distance between decision-makers and local communities and may, therefore, increase community participation, as envisaged by the 2019 water law. • allow feedback on the system-wide rules for revision when needed and this may increase the robustness of the system and reduce the cost of its coordination. • enable working rules to be devised to better suit the reality of the local context. • reduce transaction costs (seeking information, monitoring, enforcement and coordination). • ensure that failure in one unit has little effect on the performance of system-wide management and, when failure occurs and, if needed, enable timely intervention by level directly above. Limitations and risks: • Staff currently working in the lowest levels do not have the capacity and skills necessary to ensure local compliance with system-wide rules and, thus, more investment in their education and training many be necessary. • Formation of subsidiary units will take time and their operation might be challenged by conflicts of interest among different agencies in relation to budgets and development projects. Strong central direction may be necessary.
2. Clear registration system of all types of water users and use rights that facilitate a sharing system consistent with hydrological conditions. In Indonesia, this will require registration systems that ensure that: • Individual group entitlements are registered at the lowest level in the hierarchy registry and that these registries are kept current.

	• The water use entitlements or rights are defined as shares and the volume to be made available at any point in time defined as a function of water availability in parallel with a maximum limit on the volume that may be taken in normal conditions and an arrangement that unambiguously sets allocation priorities that must be followed during times of scarcity. • Permitted points of extraction are defined and it is understood that extraction or diversion from any other location is illegal. • The form, nature of use permit and the license period is easily identified and separated from the mechanisms used to determine shares and make allocations. • Use rights, responsibilities and obligations are attached to the use permit and/or license and not to the entitlement or water right. Under the current water law, smallholder farmers in the existing irrigation system do not need a license to take and use water. It is assumed, as is the case with the previous water law, under the new water law, water entitlements will be given to WUA and not given to an individual. Currently, two types of WUAs exist in the province. The first type concerns WUAs which are listed with and legalized by a notary. The second type refers to WUAs which are legalized by the head of the village. It is recommended that all WUAs be legalized by a notary and be registered in the IDs. This will be more costly for WUAs/farmers but will provide WUAs with the confidence necessary to make local decisions as they will have the same legal standing as licensed users. There is an opportunity for WUAs to engage companies which are working in their area to facilitate their association with Corporate Social Responsibility (CSR) program in relation to this issue. Alternatively, they can find support from local universities with law faculties through universities' Community Service program.
3.	**Clear and transparent sharing adjustment rules, which enable the system to respond and adapt to changes in the conditions affecting water availability.** In Indonesia, this will require that water shares are defined as a function of water availability and that volumetric allocations are made in a manner that automatically adjusts with seasonal variability and local flow conditions. However, if the change is rapid and permanent, an adjustment framework which deals with re-defining and/or allows re-assignment of water entitlements or shares may be necessary. The 2019 Water Law currently does not provide enough support for a framework that facilitates adjustments in water sharing. The only type of re-allocation that is allowed is when a river basin still has enough water available to support use in a nearby area without reducing use within the existing area. This relatively rigid system makes it difficult if not impossible for any region to adjust as conditions change. Rather than restricting transfer, which increases opportunistic behaviour by state agents and private actors to encourage system failure in a manner that adversely affects smallholder farmers, it is more efficient and more equitable to facilitate users to voluntarily transfer entitlements. These transfers can be recorded either by the management authority of a water pool where the transfer is required or by a central authority. Control as to whether or not the transfer occurs, however, should be left to the local authority on the condition that they approved only in a manner that complies with pre-defined system-wide rules.

5.5.3 Where to from here

One of the main conclusion from this thesis is the idea that the order of Ostrom's principles needs to be changed and, specifically, that her last principle be put first – whenever the list is discussed. CPR governance arrangements need to be nested within an agreed set of hierarchical arrangements and not have a hierarchical structure imposed on them after all the other principles have been locked in. The structure chosen to operationalize this nested principle must not allow overlap. That is, and as set out in Ostrom's current first principle, the boundaries must be clear, so that full accounting of the interactions between the nests is possible and it is always clear who is responsible for what.

It has been only four months since Indonesia's new water law was promulgated. Many regulations still need to be written to address the intended outcomes of the water law and also to identify and fill the gaps at national and regional levels not covered by the law. As a result, and with an eye to pragmatism, it may be politically easier and less costly to search for ways to implement this thesis' recommendations as regulations as they are developed rather than attempting to go back and amend the recently released 2019 water law. With this outcome in mind, one or more river basin authorities like the BWS IV Sulawesi or the Provincial Water Resource Management could use one of its basins or catchments to pilot-test the necessary reforms. If this approach is taken, it would enable the development of the administrative capacity and experience necessary to allow full implementation. Finally, no matter how good a suite of institutional arrangements are, without monitoring and enforcement the system is bound to fail. The above recommendations need to begin with a focus on monitoring and enforcement.

5.6 Limitations and the way forward

In a study that makes use of qualitative data, especially in the meta-analysis in **Chapter 2**, the coding process usually involves three or more researchers. However, this is not feasible in a PhD thesis; conducting solo coding is therefore unavoidable. Therefore, undertaking inter-reliability coding to avoid personal bias was not possible. To mitigate this limitation, an iterative coding process was adopted, as presented in **Chapter 2.** This enabled the use of various methods to reduce arbitrariness in the calibration process. In addition, given the highly skewed nature of the data collected, it suggests that there could be a case for more fine-grained analysis. However, it was only possible within this thesis to identify relationships between broad, very fuzzy, concepts. It would be interesting for future analysis to compare the results of the same approach when applied to different types of common-pool resources. Currently, numerous studies of various types of CPR institutions are readily available, thus a meta-analysis using fs/QCA is possible.

Further study on the change in water-use pattern and allocation and its effect on agrarian change and rural transformation is also important to shed light on the future direction of irrigation develoopent and agricultural policy in general in Indonesia. Multidiciplinary approach is needed to understand the overall situation, how the farm households adapt to such changes, or whether the current rice based policy is still relevant.

Finally, apart from the empirical analysis presented in this thesis, the study contributes to the theoretical debate on CPR governance. Its findings agree with Cox et al.'s. (2010) observation that Ostrom's DPs can be used as a diagnostic instrument. To be more effective, the analysis needs to start from the nested perspective and to unpack the design principles into elements that fit with the characteristics of CPR and the objectives of human interaction within that CPR.

Water is unique when compared to other types of CPR like fisheries and forests. Water has multiple values and uses. Moreover, it tends to flow in one direction from upstream to downstream locations. Therefore, and when not evaporated or transpired, water can be used and re-used many times. Also, supplies can vary rapidly and in terms of place where it can be accessed and in quality (Hanemann, 2006). These unique features of water suggest the need for the development of a water-specific version set of principles in a form that can be workshopped, agreed to by participants and then published.

Given the opportunity, I would welcome the chance to develop a water-specific adaptation of Ostrom's Design Principles for further consideration and development by interested parties. Water is critical to the future of humankind. Much more work on governance, allocation and management arrangements is needed.

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Appendices

Appendix 1. Description of fuzzy-set, scoring and calibration

Table A1: List of fuzzy-set definitions, scores, calibrated score and scoring criteria.

DP	Fuzzy set	Definition of fuzzy-set for inclusion criteria	Score	Calibration	Scoring criteria
BOUND	1.1. Water use rights are defined as proportional share and equitable	Water use rights are defined clearly as an ongoing proportional share. Water abstraction is regulated. Rules are respected in all seasons, including droughts. Exclusion rules are clear and not contested	0.62	1	Security of tenure Equitability Predictability (Matthews 2004, Howe, Schurmeier, and Shaw 1986) Proportionality (OECD 2015, von Benda-Beckmann 2007)
	1.2. Water use rights are clear but inequitable	Water use rights are clearly defined as an access entitlement for a fixed time, to irrigate a maximum area or take a maximum volume. Water abstraction is regulated. For some users, the right to access water may be reduced or denied especially during shortage period or as development occurs	0.26	0.33	
	1.3. Water use rights are not clear and inequitable	Legitimate users may be not defined and water abstraction is unregulated. Robust exclusion is difficult	0.11	0	
LOCCON	2A.1. Proportional and flexible allocation rules	Resource allocation rules encourage efficient use and investment as conditions change.	0.57	1	Predictability Transferability Equitability (Howe, Schurmeier, and Shaw 1986) Reliability (Matthews 2004)
	2A.2. Proportional but inefficient allocation rules	Resource allocation rules can be varied but do not allow efficient use and investment as conditions change	0.37	0.67	
	2A.3. Use and allocation rules inconsistent with local conditions	Resource allocation rules are inflexible and encourage resource depletion and/or degradation as conditions change	0.06	0	

					Proportionality (OECD 2015).
BENCOST	2B.1. Full cost recovery with equity	User contributions (in kind or cash) reflect the full costs of O&M. The distribution of contributions is proportional to user benefit.	0.46	1	Equity Sustainability (Ostrom 1990a), Predictability
	2B.2. Partial cost recovery with equity	User contributions (in kind or cash) are less than the full cost of O&M. However, the distribution of these contributions is proportional to the benefit received.	0.30	0.67	
	2B.3. Full cost recovery but inequitable	User contributions (in kind or cash) to the irrigation system reflect the full cost of O&M but the distribution of contributions is not in proportion to the benefit received.	0.18	0.33	
	2B.4. Partial cost recovery but inequitable	User contributions (in kind or cash) are less than the full cost of O&M. But, the distribution of these contributions is not in proportion to the benefit received.	0.06	0	
COLGOVE	3.1. Individual participation	All or nearly all users are involved in the lead up to a significant revision of an operational rules.	0.53	1	Transparency Accountability Trust
	3.2. Representative participation	Significant decisions typically made via a board or committee chosen from or by different user groups. In the case of a small group/village, decisions can be made by respected leader(s) of the group or head of a village. Consultation is selective.	0.34	0.67	
	3.3. Unaccountable participation	Decision making process associated with a rule change involves certain individuals. Typically, the consultation process does not involve the full spectrum of users.	0.08	0.33	
	3.4. No or very limited participation	Individual users have no guaranteed way to participate or engage in rule making processes.	0.05	0	

USERMON	4A.1. Monitors are accountable and have sufficient capacity	System encourages self-monitoring. Official monitoring capacity is sufficient to track use at the user level. Rule breaches are reported and dealt with in an efficient manner	0.77	1	Transparency Accountability Enforcement capacity
	4A.2. Capacity of monitors in inadequate	Official monitoring capacity is inadequate and/or breach enforcement is selective.	0.16	0.33	
	4A.3. No effective monitoring	Compliance with rules is not monitored or enforced.	0.07	0	
SYSTMON	4B.1. Comprehensive monitoring	Comprehensive monitoring of water resource condition and status is in place and results are accessible to all in a timely manner.	0.68	1	Transparency Reliability Easily accessible
	4B.2. Inadequate monitoring	Monitoring exists but less effective or not available in a timely manner.	0.26	0.33	
	4B.3. No effective monitoring	Comprehensive monitoring arrangements are not in place.	0.06	0	
GRADSAN	5.1. Graduated sanctions exist and are enforced	Graduated sanction system is in place and applied as required. Enforcement system may include community shaming and other sanctions.	0.74	1	Transparency. Enforcement capacity. Predictability, Proportionality
	5.2. Graduated sanction exist but enforcement is weak	Graduated sanctions are in place but all but the very weakest sanctions are rarely applied – even though significant breaches occur.	0.18	0.33	
	5.3. Rules for graduated sanction are not clear	Sanctions are rarely implemented even though non-compliance is common. Typically, no graduated sanction system is in place.	0.08	0	
CONFRES	6.1. Local CRM	Rapid and low cost conflict resolution mechanisms are locally accessible.	0.50	1	Rapid Easily accessible Low cost
	6.2 CRM through a court	Conflict mechanism require appeal to a higher level authority or through formal court process	0.26	0.67	

	6.3 Local CRM but ~~difficult to access~~ less effective	Conflict resolution mechanisms are locally accessible but less effective to prevent further conflict.	0.19	0.33	Effectiveness
	6.4. No CRM	No CRM process available. Conflict is common and usually favour the strongest party.	0.04	0	
RIGHT	7.1. Right to self-organise within a defined framework	Local users have the rights to organise themselves without compromising the agreed system-wide rules	0.59	1	Acceptability (Dinar, Rosegrant, and Meinzen-Dick 1997) Legitimacy Autonomy
	7.2. Full right to organise and over-ride system wide guidelines	Users have the right to organise and implement their operational rules in a manner that violates system-wide	0.35	0.67	
	7.3. No right to self-organise	Users have no means to organise and devise their own operational rules.	0.07	0	
NESTENT	8.1. Effective vertical and horizontal coordination structure exist	Effective vertical and horizontal coordination exists with a clear distribution of authority and task responsibilities.	0.58	1	Accountability Transparency Administrative efficiency
	8.2. Coordination structures is flawed but processes ensure accountability	Effective coordination is imperfect and includes only exist vertically or horizontally	0.29	0.67	
	8.3. Coordination structures lack accountability	Vertical and horizontal link exist but lack of accountability and transparency. Rule enforcement is lax and violations are common.	0.09	0.33	
	8.4. Coordination structures don't work	No effective vertical and horizontal coordination. No accountability.	0.05	0	

Table A2: List fuzzy set for the outcome, score, calibrated score and scoring criteria

Outcome	Fuzzy-set	Definition of fuzzy-set for inclusion criteria	Score	Calibration	Criteria
Robust institution (RI)	Robust	System persists and sustains productive use of the irrigation system and water resources. Distribution systems are well maintained and function well under duress. Conflicts, when they occur, tend to be resolved. The system is seen to be equitable and encourages efficient use and investment.	0.74	1	Adaptability Sustainability Equitability
	Fragile ("robust to what is common or anticipated but potentially fragile to what is rare or unanticipated")	Self-governance arrangements work under existing environments but are not designed so as to allow efficient and equitable management of significant changes in demand for or supply of water	0.19	0.33	
	Fail	Institution is dis-functional or non-existent. There is high conflict over water resources. Accusations of inequity are common. Resource depletion or degradation is common.	0.07	0	

Appendix 2. Truth Table Analysis

Table A3: Truth table analysis

BOUND	LOCCON	BENCOST	COLGOVE	USERMON	SYSTMON	GRADSAN	CONFRES	RIGHTORG	NESTENT	ROBUST	CASE ID	Raw Consist.
1	1	1	1	1	1	1	1	1	1	1	Alicante, Balinese Subak, Busao CIS, Chaisombat Muangfai, Culebra Asequias, Eastern La Mancha, Karya Mandiri, La Vega De Valencia, Murcia & Orihuela, Porotog, Sacaba, Soprong Muangfai, Taiwan IA, Taos Valley, Tihingan Subak, Twyford Cooperative, Utah Valley	1
1	1	1	1	1	1	0	1	1	1	1	Falaj Al-Khatmeen, Nabargram, Nishikanbara, Nothern Colorado, Sidi Okba, Tharigat watersed, Zanjera Danum	1
1	1	1	1	1	1	1	1	1	0	1	Huaynacotas, Masai, ORIC, Sanghar Lahar	1
1	1	1	1	1	1	0	1	1	0	1	Ghayl, Madarounfa, Pongsak Muangfai	1
1	1	1	1	1	1	1	0	1	0	1	Raj Kulo, Thulo Kulo	1
1	1	1	1	1	1	0	0	1	1	1	Ghazi Qanat, Shirgin	1
1	1	0	1	1	1	1	1	1	1	1	Bada, Old Valencia	1
0	1	1	1	1	1	1	0	1	0	1	Nshara	1
1	1	0	1	1	1	1	0	1	1	1	Marakwet	1
1	1	1	1	1	1	1	0	1	1	1	Contemporary Subak	1
1	1	0	1	1	1	0	1	1	1	1	Wadi Laba	1
1	1	1	0	1	1	1	1	1	1	1	Bahr Seila	1
0	1	0	1	1	1	1	1	1	1	1	Mkanyeni	1
0	0	0	1	1	0	1	1	1	0	0	Lombok Subak	0.744361
0	1	1	1	1	0	1	1	1	1	0	Likii WRUA	0.744361
0	0	1	1	1	0	0	1	1	0	0	Saint Raphael	0.66
0	1	1	1	1	0	1	1	1	0	0	Quashini, Wang village, Wen Village	0.492537
0	1	0	0	0	0	0	1	1	0	0	Northern Afghanistan	0.492537
0	0	0	1	0	1	0	1	1	1	0	Taita	0.33
0	0	0	0	0	0	0	0	0	0	0	Bulgarian IS, MIRS Kwa Zulu Natal, Nickerie, Yaqut village	0
0	0	0	0	0	0	0	1	0	0	0	Gnangara aquifer, Kuhl	0
0	0	1	0	0	0	0	1	0	0	0	Qorir SSI, Western La Mancha	0
0	1	1	0	0	1	0	1	0	0	0	Jordan Valley WUA	0
0	0	0	1	0	0	0	1	0	1	0	Bida	0
0	0	0	0	0	0	0	1	1	1	0	Mendoza	0
row 26, …, 1024 (logical reminders)											-	

Appendix 3. Supplementary material.

Supplementary material: Robust irrigation institution: A global comparison

1. Coding process

Due to the limited resources, the coding process was done individually by the primary author, thus interceding reliability cannot be performed. Being aware of the potential bias of individual coder, the coding process was done with a strict process as follows:

1. Building familiarity with the case study. This was done at the beginning of the literature review and data collection, to understand the nature of small-scale traditional irrigation systems.
2. Identifying the fuzzy-set concept of the conditions and the outcome.
3. Importing data from Endnote to Nvivo
4. The first filter (cover to cover) of the first batch of the case study and coded according to the first coding theme.
5. Revisit the fuzzy-concept.
6. Based on the study material, the fuzzy-concept was adjusted to enable all the materials were covered and minimized the missing data.
7. Re-coded the materials based on the refined fuzzy concept.
8. Retrieving more materials with snowball sampling and exporting to Nvivo.
9. Coding the new materials.
10. Whenever we gain new insight into the case materials, we revisit the fuzzy-concept and (re)coded all the materials accordingly.
11. Coding summary by code and by file reports were used to compare each case to ensure consistency of systematic coding.
12. Running analysis and compare the result with the coding if there was a conflicting issue.
13. Missing data on outcome was dropped.
14. The process was done iteratively.

2. Fuzzy set for ten conditions and an outcome

After the iterative process of refining the concept, we arrived at the final fuzzy-set as a coding theme for the study in Table 1 for conditions and Table 2 for the outcome.

Table 1. List of fuzzy-set for the conditions

Condition	Fuzzy set	Definition of fuzzy-set for inclusion criteria
BOUND	1.4. Water use rights are defined as proportional share and equitable	Water use rights are defined clearly as an ongoing proportional share. Water abstraction is regulated. Rules are respected in all seasons, including droughts. Exclusion rules are clear and not contested
	1.5. Water use rights are clear but inequitable	Water use rights are clearly defined as an access entitlement for a fixed time, to irrigate a maximum area or take a maximum volume. Water abstraction is regulated. For some users, the right to access water may be reduced or denied especially during shortage period or as development occurs
	1.6. Water use rights are not clear and inequitable	Legitimate users maybe not defined and water abstraction is unregulated. Robust exclusion is difficult
LOCCON	2A.1. Proportional and flexible allocation rules	Resource allocation rules encourage efficient use and investment as conditions change.
	2A.2. Proportional but inefficient allocation rules	Resource allocation rules can be varied but do not allow efficient use and investment as conditions change
	2A.3. Use and allocation rules inconsistent with local conditions	Resource allocation rules are inflexible and encourage resource depletion and/or degradation as conditions change
BENCOST	2B.1. Full cost recovery with equity	User contributions (in kind or cash) reflect the full costs of O&M. The distribution of contributions is proportional to user benefit.
	2B.2. Partial cost recovery with equity	User contributions (in kind or cash) are less than the full cost of O&M. However, the distribution of these contributions is proportional to the benefit received.
	2B.3. Full cost recovery but inequitable	User contributions (in kind or cash) to the irrigation system reflect the full cost of O&M but the distribution of contributions is not in proportion to the benefit received.
	2B.4. Partial cost recovery but inequitable	User contributions (in kind or cash) are less than the full cost of O&M. But, the distribution of these contributions is not in proportion to the benefit received.
COLGOVE	3.1. Individual participation	All or nearly all users are involved in the lead up to a significant revision of operational rules.
	3.2. Representative participation	Significant decisions typically made via a board or committee chosen from or by different user groups. In the case of a small group/village, decisions can be

		made by a respected leader(s) of the group or head of a village. Consultation is selective.
	3.3. Unaccountable participation	Decision-making process associated with a rule change involves certain individuals. Typically, the consultation process does not involve the full spectrum of users.
	3.4. No or very limited participation	Individual users have no guaranteed way to participate or engage in rulemaking processes.
USERMON	4A.1. Monitors are accountable and have sufficient capacity	The system encourages self-monitoring. Official monitoring capacity is sufficient to track use at the user level. Rule breaches are reported and dealt with in an efficient manner
	4A.2. Capacity of monitors is inadequate	Official monitoring capacity is inadequate and/or breach enforcement is selective.
	4A.3. No effective monitoring	Compliance with rules is not monitored or enforced.
SYSTMON	4B.1. Comprehensive monitoring	Comprehensive monitoring of water resource conditions and status is in place and results are accessible to all in a timely manner.
	4B.2. Inadequate monitoring	Monitoring exists but less effective or not available in a timely manner.
	4B.3. No effective monitoring	Comprehensive monitoring arrangements are not in place.
GRADSAN	5.1. Graduated sanctions exist and are enforced	Graduated sanction system is in place and applied as required. Enforcement system may include community shaming and other sanctions.
	5.2. Graduated sanction exist but enforcement is weak	Graduated sanctions are in place but all but the very weakest sanctions are rarely applied – even though significant breaches occur.
	5.3. Rules for graduated sanction are not clear	Sanctions are rarely implemented even though non-compliance is common. Typically, no graduated sanction system is in place.
CONFRES	6.1. Local CRM	Rapid and low-cost conflict resolution mechanisms are locally accessible.
	6.2 CRM through a court	Conflict mechanism requires an appeal to a higher level authority or through a formal court process
	6.3 Local CRM but less effective	Conflict resolution mechanisms are locally accessible but less effective to prevent further conflict.
	6.4. No CRM	No CRM process is available. Conflict is common and usually favour the strongest party.
RIGHT	7.1. Right to self-organise within a defined framework	Local users have the rights to organise themselves without compromising the agreed system-wide rules

	7.2. Full right to organise and over-ride system-wide guidelines	Users have the right to organise and implement their operational rules in a manner that violates system-wide
	7.3. No right to self-organise	Users have no means to organise and devise their own operational rules.
NESTENT	8.1. Effective vertical and horizontal coordination structure exist	Effective vertical and horizontal coordination exists with a clear distribution of authority and task responsibilities.
	8.2. Coordination structures are flawed but processes ensure accountability	Effective coordination is imperfect and includes only exist vertically or horizontally
	8.3. Coordination structures lack accountability	Vertical and horizontal link exist but lack of accountability and transparency. Rule enforcement is lax and violations are common.
	8.4. Coordination structures don't work	No effective vertical and horizontal coordination. No accountability.

Table 2. List of fuzzy-set for outcome

Outcome	**Fuzzy-set**	**Definition of fuzzy-set for inclusion criteria**
Robust institution (RI)	Robust	System persists and sustains productive use of the irrigation system and water resources. Distribution systems are well maintained and function well under duress. Conflicts, when they occur, tend to be resolved. The system is seen to be equitable and encourages efficient use and investment.
	Fragile	Self-governance arrangements work under existing environments but are not designed so as to allow efficient and equitable management of significant changes in demand for or supply of water
	Fail	Institution is dis-functional or non-existent. There is high conflict over water resources. Accusations of inequity are common. Resource depletion or degradation is common.

3. Addressing different time frames when coding the outcome.

The majority of the case studies examined displayed a snapshot or dominated by the conditions at the time the study was written. For cases where the institution was young (five to ten years), if the design principles had higher membership in the design principles ($0.5 < X \leq 1$) and there is evidence that the community had survived any type of crisis related to their water resources or there was indication that the case in question showed good trend to success, the case was coded as ‘robust’. If the design principles were more out than in ($0 \leq X < 0.5$), even though the author considered it a ‘success’, we coded as ‘fragile’ (more out than in). If the case did not provide enough information about the outcome, the case study was dropped.

4. Analytic hierarchic process

Data calibration is central to QCA, thus, providing transparency on calibrating procedure is highly recommended when using this method. Calibrating qualitative data, however, is an issue that has not been addressed by many. The challenge is how to turn the qualitative data into a numerical score prior to the calibration procedure. For crisp set QCA (cs/QCA) the calibration process is easier since the data is either ‘fully in’ (1) or ‘fully out (0). For the fuzzy-set QCA (fs/QCA) is more difficult since we use an additional gradation range from ‘fully in’ to ‘fully out’. Basurto and Speer (2012) and Toth et al. (2017) have offered guidance to calibrate qualitative data. However, their methods cannot be easily applied to our data, since their calibration is pre-determined before the data collection. On the other hand, we need to calibrate data after the fuzzy-set is defined. Therefore, we develop a process to structure the calibration procedure, in which we start with identifying criteria to classify the fuzzy-set into numerical category/score. The procedure is discussed in the following.

4.1 Identifying measurement criteria.

Prior calibration of the fuzzy-set, we turned the concept into a qualitative score to facilitate the calibration procedure. The criteria we turned into a fuzzy-set are presented in Table 3.

Table 3. Measurement criteria for condition and outcome.

Conditions and Outcome	Measurement criteria
Clearly defined boundaries (BOUND)	Security of tenure Equitability Predictability (Howe et al., 1986; Matthews, 2004) Proportionality (OECD, 2015; von Benda-Beckmann, 2007)
Congruence with local condition (LOCCON)	Predictability Transferability Equitability (Howe et al., 1986) Reliability (Matthews, 2004) Proportionality (OECD, 2015).
Proportional benefit and cost (BENCOST)	Equity, Sustainability (Ostrom, 1990), Predictability
Collective governance (COLGOVE)	Transparency Accountability Trust
User monitoring (USERMON)	Transparency Accountability Enforcement capacity
System monitoring (SYSTMON)	Transparency Reliability Easily accessible
Graduated sanction (GRADSAN)	Transparency. Enforcement capacity. Predictability, Proportionality
Conflict resolution mechanism (CONFRES)	Rapid Easily accessible Low cost Effectiveness
Minimum right to organise (RIGT)	Acceptability (Dinar et al., 1997) Legitimacy Autonomy
Nested enterprise (NESTENT)	Accountability Transparency Administrative efficiency
Robust institution (ROBUST)	Adaptability, Sustainability Equitability

4.2 Two-step pairwise comparison

The method is based on relative measurement for decision making (Saaty, 2008) using two steps pairwise comparison. The first level pairwise comparison is to weight the measurement criteria, and the second level of pairwise comparison is to compare the fuzzy-set based on each criterion. The fundamental scale of absolute numbers (Saaty 2008) is used for the scoring method.

Intensity of Importance	*Definition*	*Explanation*
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very,very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
1.1–1.9	When activities are very close a decimal is added to 1 to show their difference as appropriate	A better alternative way to assigning the small decimals is to compare two close activities with other widely contrasting ones, favoring the larger one a little over the smaller one when using the 1–9 values.
Reciprocals of above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A logical assumption
Measurements from ratio scales		When it is desired to use such numbers in physical applications. Alternatively, often one estimates the ratios of such magnitudes by using judgment

Figure 1. Fundamental scale for absolute numbers (Source: Saaty, 2008).

According to Saaty (1990), the weighted score is acceptable if the consistency ratio (CR) is equal or less than 0.1.

The following table is the example of the first-level pairwise comparison for *clearly defined boundaries*.

Table 4. Example of first-level pairwise ranking for weighting criteria of BOUND condition.

Criteria	Security	Proportionality	Equitability	Predictability	Weighted score
Security	1	3	2	3	0.41
Proportionality	0.33	1	0.33	0.33	0.10
Equitability	0.5	3	1	4	0.27
Predictability	0.33	3	0.25	1	0.22
λ_{max} = 4.04 CI = 0.01 CR = 0.01					

The Second-level pairwise comparison was done where the fuzzy-set for each DP was compared to each other based on the criteria above. Below is the example of pair-wise ranking between the fuzzy-set of *clearly defined boundaries* in terms of 'security of tenure'.

Table 5. Example of the second-level pairwise ranking of the fuzzy-set on BOUND condition based on 'security of tenure' criterion.

Clearly defined boundaries	A*	B	C	Weighted score
A. Water use rights are clear and equitable	1.00	4.00	9.00	0.62
B. Water use rights are clear and inequitable	0.25	1.00	5.00	0.26
C. Water use rights are not clear and equitable	0.11	0.20	1.00	0.11
λ_{max} = 3.04 CI = 0.02 CR = 0.03				

*A, B, C are the same fuzzy-set in the first row.

The pairwise comparison was repeated to each criterion, and the final score is presented in Table 7.

Table 6. Total score for the fuzzy-set of BOUND condition.

Clearly defined boundary	Criteria				Fuzzy-set score
	Security	Proportionality	Equity	Predictability	
	0.41	0.10	0.27	0.22	
A. Water use rights is clear and equitable	0.26	0.06	0.21	0.15	**0.68**
B. Water use rights is clear and inequitable	0.11	0.04	0.04	0.05	**0.23**
C. Water use rights is not clear and equitable	0.04	0.01	0.02	0.02	**0.09**

The above procedure was repeated to classify the fuzzy-set of all conditions and outcome. Table 7 presents the fuzzy scores

Table 7. List of Fuzzy definition of conditions, scores and calibrated scores and scoring criteria

DP	Fuzzy set	Definition of fuzzy-set for inclusion criteria	Score	Calibration	Scoring criteria
BOUND	1.1. Water use rights are defined as proportional share and equitable	Water use rights are defined clearly as an ongoing proportional share. Water abstraction is regulated. Rules are respected in all seasons, including droughts. Exclusion rules are clear and not contested	0.62	1	Security of tenure Equitability Predictability (Matthews 2004, Howe, Schurmeier, and Shaw 1986) Proportionality (OECD 2015, von Benda-Beckmann 2007)
	1.2. Water use rights are clear but inequitable	Water use rights are clearly defined as an access entitlement for a fixed time, to irrigate a maximum area or take a maximum volume. Water abstraction is regulated. For some users, the right to access water may be reduced or denied especially during shortage period or as development occurs	0.26	0.33	
	1.3. Water use rights are not clear and inequitable	Legitimate users may be not defined and water abstraction is unregulated. Robust exclusion is difficult	0.11	0	
LOCCON	2A.1. Proportional and flexible allocation rules	Resource allocation rules encourage efficient use and investment as conditions change.	0.57	1	Predictability Transferability Equitability (Howe, Schurmeier, and Shaw 1986) Reliability (Matthews 2004) Proportionality (OECD 2015).
	2A.2. Proportional but inefficient allocation rules	Resource allocation rules can be varied but do not allow efficient use and investment as conditions change	0.37	0.67	
	2A.3. Use and allocation rules inconsistent with local conditions	Resource allocation rules are inflexible and encourage resource depletion and/or degradation as conditions change	0.06	0	

BENCOST	2B.1. Full cost recovery with equity	User contributions (in kind or cash) reflect the full costs of O&M. The distribution of contributions is proportional to user benefit.	0.46	1	Equity Sustainability (Ostrom 1990a), Predictability
	2B.2. Partial cost recovery with equity	User contributions (in kind or cash) are less than the full cost of O&M. However, the distribution of these contributions is proportional to the benefit received.	0.30	0.67	
	2B.3. Full cost recovery but inequitable	User contributions (in kind or cash) to the irrigation system reflect the full cost of O&M but the distribution of contributions is not in proportion to the benefit received.	0.18	0.33	
	2B.4. Partial cost recovery but inequitable	User contributions (in kind or cash) are less than the full cost of O&M. But, the distribution of these contributions is not in proportion to the benefit received.	0.06	0	
COLGOVE	3.1. Individual participation	All or nearly all users are involved in the lead up to a significant revision of an operational rules.	0.53	1	Transparency Accountability Trust
	3.2. Representative participation	Significant decisions typically made via a board or committee chosen from or by different user groups. In the case of a small group/village, decisions can be made by respected leader(s) of the group or head of a village. Consultation is selective.	0.34	0.67	
	3.3. Unaccountable participation	Decision making process associated with a rule change involves certain individuals. Typically, the consultation process does not involve the full spectrum of users.	0.08	0.33	
	3.4. No or very limited participation	Individual users have no guaranteed way to participate or engage in rule making processes.	0.05	0	
USERMON	4A.1. Monitors are accountable and have sufficient capacity	System encourages self-monitoring. Official monitoring capacity is sufficient to track use at the user	0.77	1	Transparency

		level. Rule breaches are reported and dealt with in an efficient manner			Accountability Enforcement capacity
	4A.2. Capacity of monitors in inadequate	Official monitoring capacity is inadequate and/or breach enforcement is selective.	0.16	0.33	
	4A.3. No effective monitoring	Compliance with rules is not monitored or enforced.	0.07	0	
SYSTMON	4B.1. Comprehensive monitoring	Comprehensive monitoring of water resource condition and status is in place and results are accessible to all in a timely manner.	0.68	1	Transparency Reliability Easily accessible
	4B.2. Inadequate monitoring	Monitoring exists but less effective or not available in a timely manner.	0.26	0.33	
	4B.3. No effective monitoring	Comprehensive monitoring arrangements are not in place.	0.06	0	
GRADSAN	5.1. Graduated sanctions exist and are enforced	Graduated sanction system is in place and applied as required. Enforcement system may include community shaming and other sanctions.	0.74	1	Transparency. Enforcement capacity. Predictability, Proportionality
	5.2. Graduated sanction exist but enforcement is weak	Graduated sanctions are in place but all but the very weakest sanctions are rarely applied – even though significant breaches occur.	0.18	0.33	
	5.3. Rules for graduated sanction are not clear	Sanctions are rarely implemented even though non-compliance is common. Typically, no graduated sanction system is in place.	0.08	0	
CONFRES	6.1. Local CRM	Rapid and low cost conflict resolution mechanisms are locally accessible.	0.50	1	Rapid Easily accessible Low cost Effectiveness
	6.2 CRM through a court	Conflict mechanism require appeal to a higher level authority or through formal court process	0.26	0.67	
	6.3 Local CRM but less effective	Conflict resolution mechanisms are locally accessible but less effective to prevent further conflict.	0.19	0.33	

	6.4. No CRM	No CRM process available. Conflict is common and usually favour the strongest party.	0.04	0	
RIGHT	7.1. Right to self-organise within a defined framework	Local users have the rights to organise themselves without compromising the agreed system-wide rules	0.59	1	Acceptability (Dinar, Rosegrant, and Meinzen-Dick 1997) Legitimacy Autonomy
	7.2. Full right to organise and over-ride system wide guidelines	Users have the right to organise and implement their operational rules in a manner that violates system-wide	0.35	0.67	
	7.3. No right to self-organise	Users have no means to organise and devise their own operational rules.	0.07	0	
NESTENT	8.1. Effective vertical and horizontal coordination structure exist	Effective vertical and horizontal coordination exists with a clear distribution of authority and task responsibilities.	0.58	1	Accountability Transparency Administrative efficiency
	8.2. Coordination structures is flawed but processes ensure accountability	Effective coordination is imperfect and includes only exist vertically or horizontally	0.29	0.67	
	8.3. Coordination structures lack accountability	Vertical and horizontal link exist but lack of accountability and transparency. Rule enforcement is lax and violations are common.	0.09	0.33	
	8.4. Coordination structures don't work	No effective vertical and horizontal coordination. No accountability.	0.05	0	

Table 8. List of Fuzzy definioin for outcome, scores and calibration scroes and scoring criteria.

Outcome	Fuzzy-set	Definition of fuzzy-set for inclusion criteria	Score	Calibration	Criteria
Robust institution (RI)	Robust	System persists and sustains productive use of the irrigation system and water resources. Distribution systems are well maintained and function well under duress. Conflicts, when they occur, tend to be resolved. The system is seen to be equitable and encourages efficient use and investment.	0.74	1	Adaptability Sustainability Equitability
	Fragile ("robust to what is common or anticipated but potentially fragile to what is rare or unanticipated")	Self-governance arrangements work under existing environments but are not designed so as to allow efficient and equitable management of significant changes in demand for or supply of water	0.19	0.33	
	Fail	Institution is dis-functional or non-existent. There is high conflict over water resources. Accusations of inequity are common. Resource depletion or degradation is common.	0.07	0	

1) Applying the score for cases

After the systematic coding, we generated qualitative classification from the cross-tabulation in Nvivo, and turn it into the numerical score. Table 9 provided the raw data for all cases. The yellow box indicates ‘missing data’.

Table 9. Raw data

No.	Case ID	Country	BOUND	LOCCON	BENCOST	COLGOVE	USERMON	SYSTMON	GRADSAN	CONFRES	RIGHT	NESTENT	ROBUST
1	Alicante	Spain	0.68	0.57	0.46	0.34	0.77	0.69	0.74	0.5	0.59	0.58	0.74
2	Bada Spate Irrigation system	Eritrea	0.68	0.37	0.18	0.53	0.77	0.69	0.74	0.5	0.59	0.58	0.74
3	Bahr Seila Fayoum	Egypt	0.68	0.57	0.3	0.05	0.77	0.69	0.74	0.5	0.59	0.58	0.74
4	Balinese Subak	Indonesia	0.68	0.37	0.46	0.53	0.77	0.69	0.74	0.5	0.59	0.58	0.74
5	Bida Irrigation system	Nigeria	0.09	0.06	0.18	0.34	0.16	0.06	0.08	0.5	0.07	0.29	0.07
6	Bulgarian irrigation system	Bulgaria	0.09	0.06	0.06	0.05	0.07	0.06	0.08	0.04	0.07	0.05	0.07
7	Busao CIS	The Philippines	0.68	0.37	0.46	0.53	0.77	0.69	0.74	0.5	0.59	0.58	0.74
8	Chaisombat Muang Fai	Thailand	0.68	0.37	0.46	0.34	0.77	0.69	0.74	0.5	0.59	0.58	0.74
9	Contemporary Subak	Indonesia	0.68	0.37	0.3	0.53	0.77	0.69	0.74	0.19	0.59	0.29	0.74
10	Culebra Asequias	USA	0.68	0.37	0.46	0.53	0.77	0.69	0.74	0.5	0.59	0.58	0.74
11	Eastern La Mancha	Spain	0.68	0.57	0.46	0.53	0.77	0.69	0.74	0.5	0.59	0.58	0.74
12	Falaj Al-Khatmeen	Oman	0.68	0.57	0.46	0.34	0.77	0.69		0.5	0.59	0.58	0.74
13	Ghayl	Yemen	0.68	0.57	0.46	0.53	0.77	0.69		0.5	0.59	0.05	0.74
14	Ghazi qanat	Iran	0.68	0.37	0.46	0.53	0.77	0.69			0.59	0.58	0.74
15	Gnangara	Australia	0.09	0.06	0.06	0.05	0.16	0.25	0.18	0.26	0.07	0.09	0.07
16	Huaynacotas, Peru	Peru	0.68	0.37	0.46	0.34	0.77	0.69	0.74	0.5	0.59	0.05	0.74
17	JV WUAs	Jordan	0.23	0.37	0.3	0.08	0.16	0.69	0.18	0.5	0.07	0.09	0.07
18	Karya Mandiri Irrigation System	Indonesia	0.68	0.37	0.46	0.34	0.77	0.69	0.74	0.5	0.59	0.58	0.74
19	Kuhl Irrigation System Pakistan	India	0.09	0.06	0.06	0.05	0.07	0.06	0.08	0.5	0.07	0.05	0.07
20	La Vega de Valencia	Spain	0.68	0.37	0.46	0.53	0.77	0.69	0.74	0.5	0.59	0.58	0.74
21	Likii WRUA	Kenya	0.23	0.37	0.46	0.34	0.77	0.06	0.74	0.5	0.59	0.58	0.19
22	Lombok Subak	Indonesia	0.09	0.06	0.06	0.53	0.77	0.25	0.74	0.5	0.59	0.05	0.19
23	Madarounfa irrigation system	Niger	0.68	0.37	0.46	0.53	0.77	0.69		0.5	0.59	0.05	0.74
24	Marakwet irrigation system	Kenya	0.68	0.37	0.18	0.34	0.77	0.69	0.74	0.19	0.59	0.58	0.74
25	Masai Irrigation System	Tanzania	0.68	0.57	0.46	0.34	0.77	0.69	0.74	0.5	0.59	0.05	0.74
26	Mendoza	Argentina	0.23	0.06	0.06	0.08	0.16	0.25		0.5	0.59	0.58	0.07
27	Mkanyeni Furrow	Tanzania	0.23	0.37	0.18	0.53	0.77	0.69	0.74	0.5	0.59	0.58	0.74
28	MRIS KwaZulu-Natal	South Africa	0.09	0.06	0.06	0.05	0.07	0.06	0.18	0.19	0.07	0.05	0.07
29	Murcia & Orihuela	Spain	0.68	0.37	0.3	0.34	0.77	0.69	0.74	0.5	0.59	0.58	0.74
30	Nabagram irrigation system	Bangladesh	0.68	0.57	0.46	0.34	0.77	0.69		0.5	0.59	0.58	0.74
31	Nickerie irrigation	Suriname	0.09	0.06	0.06	0.05	0.07	0.06	0.08	0.04	0.07	0.09	0.07
32	Nishikanbara	Japan	0.68	0.37	0.46	0.34	0.77	0.69	0.08	0.5	0.59	0.58	0.74
33	North Afghan irrigation	Afghanistan	0.23	0.37	0.18	0.08	0.16	0.25		0.5	0.59	0.05	0.19
34	Northeastern Colorado	USA	0.68	0.57	0.46	0.34	0.77	0.69		0.26	0.59	0.58	0.74
35	Nshara Furrow	Tanzania	0.23	0.57	0.46	0.53	0.77	0.69	0.74		0.59	0.05	0.74
36	ORIC	Zimbabwe	0.68	0.37	0.46	0.34	0.77	0.69	0.74	0.5	0.59	0.05	0.74
37	Pongsak Muang Fai	Thailand	0.68	0.37	0.46	0.53	0.77	0.69	0.74	0.5	0.59	0.05	0.74
38	Porotog	Ecuador	0.68	0.37	0.3	0.34	0.77	0.69	0.74	0.5	0.59	0.29	0.74
39	Qorir SSI	Ethiopia	0.09	0.06	0.3	0.05	0.07	0.06	0.08	0.26	0.07	0.05	0.07
40	Quashini Irrigation System	Ethiopia	0.09	0.37	0.46	0.34	0.77	0.25	0.74	0.5	0.59	0.05	0.19
41	Raj Kulo	Nepal	0.68	0.37	0.46	0.53	0.77	0.69	0.74		0.59	0.05	0.74
42	Saint Raphael irrigation system	Haiti	0.23	0.06	0.3	0.34	0.77	0.06	0.18	0.26	0.59	0.05	0.19
43	Sanghar Lahr irrigation system	Pakistan	0.68	0.37	0.46	0.34	0.77	0.69	0.74	0.5	0.59	0.05	0.74
44	Shirgin	Tajikistan	0.68	0.37	0.3	0.34	0.77	0.69			0.59	0.58	0.74
45	Sidi Okba	Algeria	0.68	0.57	0.3	0.34	0.77	0.69		0.5	0.59	0.58	0.74
46	Soprong Muang Fai	Thailand	0.68	0.37	0.46	0.34	0.77	0.69	0.74	0.5	0.59	0.58	0.74
47	Taita Irrigation system	Kenya	0.09	0.06	0.18	0.34	0.16	0.69	0.18	0.26	0.59	0.29	0.19
48	Taiwan IA	Taiwan	0.68	0.37	0.3	0.34	0.77	0.69	0.74	0.5	0.59	0.58	0.74
49	Taos Valley	USA	0.68	0.37	0.46	0.53	0.77	0.69	0.74	0.26	0.59	0.58	0.74
50	Thalo Kulo	Nepal	0.68	0.57	0.46	0.53	0.77	0.69	0.74		0.59	0.05	0.74
51	Tharigat watersed	India	0.68	0.37	0.3	0.34	0.77	0.69		0.5	0.59	0.58	0.74
52	Tihingan Subak	Indonesia	0.68	0.37	0.46	0.53	0.77	0.69	0.74	0.5	0.59	0.58	0.74
53	Twyford Cooperative	New Zealand	0.68	0.57	0.46	0.53	0.77	0.69	0.74	0.26	0.59	0.58	0.74
54	Usosyumbro	Bolivia	0.68	0.37	0.46	0.53	0.77	0.69	0.74	0.5	0.59	0.58	0.74
55	Utah Valley	USA	0.68	0.37	0.46	0.53	0.77	0.69	0.74	0.5	0.59	0.58	0.74
56	Valencia	Spain	0.68	0.57	0.18	0.53	0.77	0.69	0.74	0.5	0.59	0.58	0.74
57	Wadi Laba	Eritrea	0.68	0.37	0.18	0.34	0.77	0.69		0.5	0.59	0.58	0.74
58	Wang village irrigation	China	0.23	0.37	0.46	0.34	0.77	0.06	0.74	0.5	0.35	0.09	0.19
59	Wen village irrigation system	China	0.23	0.37	0.3	0.53	0.77	0.06	0.74	0.5	0.35	0.09	0.19
60	Western Mancha	Spain	0.09	0.06	0.3	0.05	0.16	0.06	0.08	0.5	0.07	0.09	0.07
61	Yaqut village	Egypt	0.09	0.06	0.06	0.05	0.07	0.06	0.08	0.04	0.07	0.05	0.07
62	Zanjera Danum	The Philippines	0.68	0.37	0.46	0.53	0.77	0.69		0.5	0.59	0.58	0.74

5. Data calibration

This study used an indirect data calibration method. The fully in (1) was assigned to the highest fuzzy-set with the highest score, and the fully out (0) to the lowest fuzzy-set score. For the qualitative fuzzy-set, it is difficult to justify the cross-over point (0.5), and, also, cases with maximum ambiguity (0.5) will be dropped from the analysis. Thus, we use the four fuzzy-value (Ragin, 2009) and apply the middle value 'more or less in' (0.67) for cases whose score was relatively complied more to the highest score, and 'more or less out' (0.33) for cases whose score was relatively complied more to the lowest score. The missing data were assigned to the lowest score, to be able to identify and explore further in the analysis why the conditions with missing data ("0" or not in the set) can contribute to the ROBUST outcome.

Table 10. Calibrated data

Case ID	BOUND	LOCCON	BENCOST	COLGOVE	USERMON	SYSTMON	GRADSAN	CONFRES	RIGTORG	NESTENT	ROBUST
Alicante	1	1	1	0.67	1	1	1	1	1	1	1
Bada Spate Irrigation system	1	0.67	0.33	1	1	1	1	1	1	1	1
Bahr Seila Fayoum	1	1	0.67	0	1	1	1	1	1	1	1
Balinese Subak	1	0.67	1	1	1	1	1	1	1	1	1
Bida Irrigation system	0	0	0.33	0.67	0.33	0	0	1	0	0.67	0
Bulgarian irrigation system	0	0	0	0	0	0	0	0	0	0	0
Busao CIS	1	0.67	1	1	1	1	1	1	1	1	1
Chaisombat Muang Fai	1	0.67	1	0.67	1	1	1	1	1	1	1
Contemporary Subak	1	0.67	0.67	1	1	1	1	0.33	1	0.67	1
Culebra Asequias	1	0.67	1	1	1	1	1	1	1	1	1
Eastern La Mancha	1	1	1	1	1	1	1	1	1	1	1
Falaj Al-Khatmeen	1	1	1	0.67	1	1	0	1	1	1	1
Ghayl	1	1	1	1	1	1	0	1	1	0	1
Ghazi qanat	1	0.67	1	1	1	1	0	0	1	1	1
Gnangara	0	0	0	0	0.33	0.33	0.33	0.67	0	0.33	0
Huaynacotas, Peru	1	0.67	1	0.67	1	1	1	1	1	0	1
JV WUAs	0.33	0.67	0.67	0.33	0.33	1	0.33	1	0	0.33	0
Karya Mandiri Irrigation System	1	0.67	1	0.67	1	1	1	1	1	1	1
Kuhl Irrigation System Pakistan	0	0	0	0	0	0	0	1	0	0	0
La Vega de Valencia	1	0.67	1	1	1	1	1	1	1	1	1
Likii WRUA	0.33	0.67	1	0.67	1	0	1	1	1	1	0.33
Lombok Subak	0	0	0	1	1	0.33	1	1	1	0	0.33
Madarounfa irrigation system	1	0.67	1	1	1	1	0	1	1	0	1
Marakwet irrigation system	1	0.67	0.33	0.67	1	1	1	0.33	1	1	1
Masai Irrigation System	1	1	1	0.67	1	1	1	1	1	0	1
Mendoza	0.33	0	0.33	0.33	0.33	0.33	0	1	1	1	0
Mkanyeni Furrow	0.33	0.67	0.33	1	1	1	1	1	1	1	1
MRIS KwaZulu-Natal	0	0	0	0	0	0	0.33	0.33	0	0	0
Murcia & Orihuela	1	0.67	0.67	0.67	1	1	1	1	1	1	1
Nabagram irrigation system	1	1	1	0.67	1	1	0	1	1	1	1
Nickerie irrigation	0	0	0	0	0	0	0	0	0	0.33	0
Nishikanbara	1	0.67	1	0.67	1	1	0	1	1	1	1
North Afghan irrigation	0.33	0.67	0.33	0.33	0.33	0.33	0	1	1	0	0.33
Northeastern Colorado	1	1	1	0.67	1	1	0	0.67	1	1	1
Nshara Furrow	0.33	1	1	1	1	1	1	0	1	0	1
ORIC	1	0.67	1	0.67	1	1	1	1	1	0	1
Pongsak Muang Fai	1	0.67	1	1	1	1	0	1	1	0	1
Porotog	1	0.67	0.67	0.67	1	1	1	1	1	0.67	1
Qorir SSI	0	0	0.67	0	0	0	0	0.67	0	0	0
Quashini Irrigation System	0	0.67	1	0.67	1	0.33	1	1	1	0	0.33
Raj Kulo	1	0.67	1	1	1	1	1	0	1	0	1
Saint Raphael irrigation system	0.33	0	0.67	0.67	1	0	0.33	0.67	1	0	0.33
Sanghar Lahr irrigation system	1	0.67	1	0.67	1	1	1	1	1	0	1
Shirgin	1	0.67	0.67	0.67	1	1	0	0	1	1	1
Sidi Okba	1	1	0.67	0.67	1	1	0	1	1	1	1
Soprong Muang Fai	1	0.67	1	0.67	1	1	1	1	1	1	1
Taita Irrigation system	0	0	0.33	0.67	0.33	1	0.33	0.67	1	0.67	0.33
Taiwan IA	1	0.67	0.67	0.67	1	1	1	1	1	1	1
Taos Valley	1	0.67	1	1	1	1	1	0.67	1	1	1
Thalo Kulo	1	1	1	1	1	1	1	0	1	0	1
Tharigat watersed	1	0.67	0.67	0.67	1	1	0	1	1	1	1
Tihingan Subak	1	0.67	1	1	1	1	1	1	1	1	1
Twyford Cooperative	1	1	1	1	1	1	1	0.67	1	1	1
Usosyumbro	1	0.67	1	1	1	1	1	1	1	1	1
Utah Valley	1	0.67	1	1	1	1	1	1	1	1	1
Valencia	1	1	0.33	1	1	1	1	1	1	1	1
Wadi Laba	1	0.67	0.33	0.67	1	1	0	1	1	1	1
Wang village irrigation	0.33	0.67	1	0.67	1	0	1	1	0.67	0.33	0.33
Wen village irrigation system	0.33	0.67	0.67	1	1	0	1	1	0.67	0.33	0.33
Western Mancha	0	0	0.67	0	0.33	0	0	1	0	0.33	0
Yaqut village	0	0	0	0	0	0	0	0	0	0	0
Zanjera Danum	1	0.67	1	1	1	1	0	1	1	1	1

6. Result of fs/QCA

6.1 *Necessary condition analysis*

Analysis of Necessary Conditions

Outcome variable: ROBUST

Conditions tested:

	Consistency	Coverage
BOUND	0.948948	0.984990
LOCCON	0.761393	0.936153
BENCOST	0.861525	0.880036
COLGOVE	0.833479	0.896958
USERMON	1.000000	0.889495
SYSTMON	0.971078	0.950054
GRADSAN	0.707932	0.881583
CONFRES	0.839395	0.771135
RIGHT	1.000000	0.888976
NESTENT	0.737511	0.893787

Analysis of Necessary Conditions

Outcome variable: ~ROBUST

Conditions tested:

	Consistency	Coverage
~BOUND	0.959658	0.870771
~LOCCON	0.855134	0.562299
~BENCOST	0.672372	0.635104
~COLGOVE	0.732885	0.612047
~USERMON	0.653423	1.000000
~SYSTMON	0.857579	0.914007
~GRADSAN	0.734719	0.474162
~CONFRES	0.305012	0.405032
~RIGHT	0.651589	1.000000
~NESTENT	0.755501	0.507806

6.2 *Analysis of sufficiency condition for ROBUST outcome*

Table 11. Truth table.

BOUND	LOCCON	BENCOST	COLGOVE	USERMON	SYSTMON	GRADSAN	CONFRES	RIGHTORG	NESTENT	ROBUST	CASE ID	Raw Consist.
1	1	1	1	1	1	1	1	1	1	1	Alicante, Balinese Subak, Busao CIS, Chaisombat Muangfai, Culebra Asequias, Eastern La Mancha, Karya Mandiri, La Vega De Valencia, Murcia & Orihuela, Porotog, Sacaba, Soprong Muangfai, Taiwan IA, Taos Valley, Tihingan Subak, Twyford Cooperative, Utah Valley	1
1	1	1	1	1	1	0	1	1	1	1	Falaj Al-Khatmeen, Nabargram, Nishikanbara, Nothern Colorado, Sidi Okba, Tharigat watersed, Zanjera Danum	1
1	1	1	1	1	1	1	1	1	0	1	Huaynacotas, Masai, ORIC, Sanghar Lahar	1
1	1	1	1	1	1	0	1	1	0	1	Ghayl, Madarounfa, Pongsak Muangfai	1
1	1	1	1	1	1	1	0	1	0	1	Raj Kulo, Thulo Kulo	1
1	1	1	1	1	1	0	0	1	1	1	Ghazi Qanat, Shirgin	1
1	1	0	1	1	1	1	1	1	1	1	Bada, Old Valencia	1
0	1	1	1	1	1	1	0	1	0	1	Nshara	1
1	1	0	1	1	1	1	0	1	1	1	Marakwet	1
1	1	1	1	1	1	1	0	1	1	1	Contemporary Subak	1
1	1	0	1	1	1	0	1	1	1	1	Wadi Laba	1

1	1	1	0	1	1	1	1	1	1	1	Bahr Seila	1
0	1	0	1	1	1	1	1	1	1	1	Mkanyeni	1
0	0	0	1	1	0	1	1	1	0	0	Lombok Subak	0.744361
0	1	1	1	1	0	1	1	1	1	0	Likii WRUA	0.744361
0	0	1	1	1	0	0	1	1	0	0	Saint Raphael	0.66
0	1	1	1	1	0	1	1	1	0	0	Quashini, Wang village, Wen Village	0.492537
0	1	0	0	0	0	0	1	1	0	0	Northern Afghanistan	0.492537
0	0	0	1	0	1	0	1	1	1	0	Taita	0.33
0	0	0	0	0	0	0	0	0	0	0	Bulgarian IS, MIRS Kwa Zulu Natal, Nickerie, Yaqut village	0
0	0	0	0	0	0	0	1	0	0	0	Gnangara aquifer, Kuhl	0
0	0	1	0	0	0	0	1	0	0	0	Qorir SSI, Western La Mancha	0
0	1	1	0	0	1	0	1	0	0	0	Jordan Valley WUA	0
0	0	0	1	0	0	0	1	0	1	0	Bida	0
0	0	0	0	0	0	0	1	1	1	0	Mendoza	0
row 26, …, 1024 (logical reminders)											-	

Parsimonious solution

```
*********************
*TRUTH TABLE ANALYSIS*
*********************

File:  //uofa/USERS$/users8/a1697278/Data/Ostrom paper/100419_62cases_fsQCA.csv
Model: ROBUST = f(BOUND, LOCCON, BENCOST, COLGOVE, USERMON, SYSTMON, GRADSAN, CONFRES, RIGHT, NESTENT)
Algorithm: Quine-McCluskey

--- PARSIMONIOUS SOLUTION ---
frequency cutoff: 1
consistency cutoff: 1
                              raw        unique
                            coverage    coverage    consistency
                           ----------  ----------  ----------
USERMON*SYSTMON            0.971078    0.231376    0.97815
LOCCON*SYSTMON*RIGHT       0.739702    0           1

solution coverage: 0.971078
solution consistency: 0.97815
```

Solution	Case
USERMON*SYSTMON	Alicante (1,1), Bada Spate (1,1), Bahr Seila Fayoum (1,1), Balinese Subak (1,1), Busao CIS (1,1), Chaisombat Muang Fai (1,1), Contemporary Subak (1,1), Culebra Asequias (1,1), Eastern La Mancha (1,1), Falaj Al Khatmeen (1,1), Ghayl (1,1), Ghaziqanat (1,1), Huaynacotas (1,1), Karya Mandiri (1,1), LaVega de Valencia (1,1), Madarounfa (1,1), Marakwet (1,1), Masai (1,1), Mkanyeni (1,1),
LOCCON*SYSTMON*RIGT	Alicante (1,1), Masai (1,1), Bahr Seila Fayoum (1,1), EasternLaMancha (1,1), Falaj Al Khatmeen (1,1), Ghayl (1,1), Nabagram (1,1), Northeastern Colorado (1,1), Nshara Furrow (1,1), Sidi Okba (1,1), Twyford Cooperative (1,1), Thalo Kulo (1,1), Valencia (1,1),

	Ghazi qanat (0.67,1), Huaynacotas (0.67,1), Karya Mandiri (0.67,1), La Vega deValencia (0.67,1), Madarounfai (0.67,1), Marakwet (0.67,1), Mkanyeni (0.67,1)

Intermediate solution

```
*********************
*TRUTH TABLE ANALYSIS*
*********************

File:  //uofa/USERS$/users8/a1697278/Data/Ostrom paper/100419_62cases_fsQCA.csv
Model: ROBUST = f(BOUND, LOCCON, BENCOST, COLGOVE, USERMON, SYSTMON, GRADSAN, CONFRES, RIGHT, NESTENT)
Algorithm: Quine-McCluskey

--- INTERMEDIATE SOLUTION ---
frequency cutoff: 1
consistency cutoff: 1
Assumptions:
                                                                  raw       unique
                                                               coverage    coverage   consistency
                                                              ----------  ----------  ----------
BOUND*LOCCON*BENCOST*COLGOVE*USERMON*SYSTMON*CONFRES*RIGHT   0.520158    0.117222    1
BOUND*LOCCON*BENCOST*COLGOVE*USERMON*SYSTMON*RIGHT*NESTENT   0.446976    0.0293602   1
BOUND*LOCCON*COLGOVE*USERMON*SYSTMON*GRADSAN*RIGHT*NESTENT   0.337204    0.00744963  1
BOUND*LOCCON*COLGOVE*USERMON*SYSTMON*CONFRES*RIGHT*NESTENT   0.432515    0.00744963  1
LOCCON*BENCOST*COLGOVE*USERMON*SYSTMON*GRADSAN*~CONFRES*RIGHT*~NESTENT   0.0657318   0.0585013   1
LOCCON*~BENCOST*COLGOVE*USERMON*SYSTMON*GRADSAN*CONFRES*RIGHT*NESTENT    0.0801928   0.00744963  1
BOUND*LOCCON*BENCOST*USERMON*SYSTMON*GRADSAN*CONFRES*RIGHT*NESTENT       0.314855    0.0219106   1

solution coverage: 0.689088
solution consistency: 1
```

Solution	Case
BOUND*LOCCON* BENCOST*COLGOVE* USERMON* SYSTMON* CONFRES*RIGHT	Eastern La Mancha (1,1), Ghayl (1,1), Alicante (0.67,1), Balinese Subak (0.67,1), Busao CIS (0.67,1), Chaisombat Muang Fai (0.67,1), Culebra Asequias (0.67,1), Falaj Al Khatmeen (0.67,1), Huaynacotas (0.67,1), Karya Mandiri (0.67,1), La Vega de Valencia (0.67,1), Madarounfa (0.67,1), Masai (0.67,1), Murcia & Orihuela (0.67,1), Nabagram (0.67,1), Nishikanbara (0.67,1), Northeastern Colorado (0.67,1), ORIC (0.67,1), Pongsak Muang Fai (0.67,1), Porotog (0.67,1)
BOUND*LOCCON* BENCOST*COLGOVE* USERMON*SYSTMON* RIGHT*NESTENT	Eastern La Mancha (1,1), Twyford Cooperative (1,1), Alicante (0.67,1), Balinese Subak (0.67,1), Busao CIS (0.67,1), Chaisombat Muang Fai (0.67,1), Contemporary Subak (0.67,1), Culebra Asequias (0.67,1), Falaj Al Khatmeen (0.67,1), Ghazi qanat (0.67,1), KaryaMandiriIrrigationSystem (0.67,1), LaVegadeValencia (0.67,1), Murci a &Orihuela (0.67,1), Nabagram (0.67,1), Nishikanbara (0.67,1), Northeastern Colorado (0.67,1), Porotog (0.67,1), Shirgin (0.67,1), Sidi Okba (0.67,1), Soprong Muang Fai (0.67,1)
BOUND*LOCCON* COLGOVE*USERMON*	Eastern La Mancha (1,1),Twyford Cooperative (1,1), Valencia (1,1), Alicante (0.67,1),

SYSTMON* GRADSAN* RIGHT*NESTENT	Bada Spate (0.67,1), Balinese Subak (0.67,1), Busao CIS (0.67,1), Chaisombat Muang Fai (0.67,1), Contemporary Subak (0.67,1), Culebra Asequias (0.67,1), Karya Mandiri 0.67,1), La Vegade Valencia (0.67,1), Marakwet (0.67,1), Murcia & Orihuela (0.67,1), Porotog (0.67,1), Soprong Muang Fai (0.67,1), TaiwanIA (0.67,1), Taos Valley (0.67,1), Tihingan Subak (0.67,1), Usosy Umbro Cochabamba (0.67,1)
BOUND*LOCCON* COLGOVE*USERMON* SYSTMON* CONFRES* RIGHT*NESTENT	Eastern La Mancha (1,1), Valencia (1,1), Alicante (0.67,1), Bada Spate (0.67,1), Balinese Subak (0.67,1), Busao CIS (0.67,1), Chaisombat Muang Fai (0.67,1), Culebra Asequias (0.67,1), Falaj Al Khatmeen (0.67,1), Karya Mandiri I (0.67,1), La Vegade Valencia (0.67,1), Murcia & Orihuela (0.67,1), Nabagrami (0.67,1), Nishikanbara (0.67,1), Northeastern Colorado (0.67,1), Porotog (0.67,1), Sidi Okba (0.67,1), Soprong Muang Fai (0.67,1), Taiwan IA (0.67,1), TaosValley (0.67,1)
LOCCON*BENCOST*COLGOVE* USERMON*SYSTMON*GRADSAN* ~CONFRES*RIGHT*~NESTENT	Nshara Furrow (1,1), Thalo Kulo (1,1), Raj Kulo (0.67,1)
LOCCON*~BENCOST*COLGOVE* USERMON*SYSTMON*GRADSAN* CONFRES*RIGHT*NESTENT	Bada Spate (0.67,1), Mkanyeni (0.67,1), Valencia (0.67,1)
BOUND*LOCCON* BENCOST*USERMON* YSTMON*GRADSAN* CONFRES*RIGHT*NESTENT	Alicante (1,1), Eastern La Mancha (1,1), Bahr Seila Fayoum (0.67,1), Balinese Subak (0.67,1), Busao CIS (0.67,1), Chaisombat Muang Fai (0.67,1), Culebra Asequias (0.67,1), Karya Mandiri (0.67,1), La Vega de Valencia (0.67,1), Murcia & Orihuela (0.67,1), Porotog (0.67,1), Soprong Muang Fai (0.67,1), Taiwan IA (0.67,1), Taos Valley (0.67,1), Tihingan Subak (0.67,1), Twyford Cooperative (0.67,1), Usosy Umbro Cochabamba (0.67,1), Utah Valley (0.67,1)

6.3 Analysis of sufficiency conditions for ~ROBUST outcome

Parsimonious solution

```
*********************
*TRUTH TABLE ANALYSIS*
*********************

File:  //uofa/USERS$/users8/a1697278/Data/Ostrom paper/100419_62cases_fsQCA.csv
Model: ~ROBUST = f(BOUND, LOCCON, BENCOST, COLGOVE, USERMON, SYSTMON, GRADSAN, CONFRES, RIGTORG, NESTENT)
Algorithm: Quine-McCluskey

--- PARSIMONIOUS SOLUTION ---
frequency cutoff: 1
consistency cutoff: 1
                       raw       unique
                     coverage   coverage   consistency
                    ---------- ---------- ----------
~SYSTMON            0.857579   0.224939   0.914007
~BOUND*~GRADSAN     0.714548   0.0819071  1

solution coverage: 0.939487
solution consistency: 0.920911


Cases with greater than 0.5 membership in term ~SYSTMON: BidaIrrigationsystem (1,1),
  Bulgarianirrigationsystem (1,1), KuhlIrrigationSystem (1,1), LikiiWRUA (1,0.67),
  MRISKwaZulu-Natal (1,1), Nickerieirrigation (1,1), QorirSSI (1,1),
  SaintRaphaelirrigationsystem (1,0.67), Wangvillageirrigation (1,0.67), Wenvillageirrigationsystem (1,0.67),
  WesternMancha (1,1), Yaqutvillage (1,1), Gnangara (0.67,1),
  LombokSubak (0.67,0.67), Mendoza (0.67,1), NorthAfghanirrigation (0.67,0.67),
  QuashiniIrrigationSystem (0.67,0.67)
Cases with greater than 0.5 membership in term ~BOUND*~GRADSAN: BidaIrrigationsystem (1,1),
  Bulgarianirrigationsystem (1,1), KuhlIrrigationSystem (1,1), Nickerieirrigation (1,1),
  QorirSSI (1,1), WesternMancha (1,1), Yaqutvillage (1,1),
  Gnangara (0.67,1), JVWUAs (0.67,1), Mendoza (0.67,1),
  MRISKwaZulu-Natal (0.67,1), NorthAfghanirrigation (0.67,0.67), SaintRaphaelirrigationsystem (0.67,0.67),
  TaitaIrrigationsystem (0.67,0.67)
```

Intermediate solution

```
*********************
*TRUTH TABLE ANALYSIS*
*********************

File:  //uofa/USERS$/users8/a1697278/Data/Ostrom paper/100419_62cases_fsQCA.csv
Model: ~ROBUST = f(BOUND, LOCCON, BENCOST, COLGOVE, USERMON, SYSTMON, GRADSAN, CONFRES, RIGHT, NESTENT)
Algorithm: Quine-McCluskey

--- INTERMEDIATE SOLUTION ---
frequency cutoff: 1
consistency cutoff: 1
Assumptions:
                                                                                 raw       unique
                                                                               coverage   coverage   consistency
                                                                              ---------- ---------- ----------
~BOUND*~LOCCON*~BENCOST*~COLGOVE*~USERMON*~SYSTMON*~GRADSAN*~RIGHT*~NESTENT        0.366748   0.183985    1
~BOUND*~LOCCON*~COLGOVE*~USERMON*~SYSTMON*~GRADSAN*CONFRES*~RIGHT*~NESTENT         0.224328   0.0415648   1
~BOUND*LOCCON*BENCOST*COLGOVE*USERMON*~SYSTMON*GRADSAN*CONFRES*RIGHT               0.163814   0.143643    1
~BOUND*LOCCON*~BENCOST*~COLGOVE*~USERMON*~SYSTMON*~GRADSAN*CONFRES*RIGHT*~NESTENT  0.0409535  0.0207824   1
~BOUND*~LOCCON*~BENCOST*COLGOVE*~USERMON*~SYSTMON*~GRADSAN*CONFRES*~RIGHT*NESTENT  0.0409535  0.0207824   1
~BOUND*~LOCCON*~BENCOST*~COLGOVE*~USERMON*~SYSTMON*~GRADSAN*CONFRES*RIGHT*NESTENT  0.0409535  0.0207824   1
~BOUND*LOCCON*BENCOST*~COLGOVE*~USERMON*SYSTMON*~GRADSAN*CONFRES*~RIGHT*~NESTENT   0.0409535  0.0409536   1
~BOUND*~LOCCON*BENCOST*COLGOVE*USERMON*~SYSTMON*~GRADSAN*CONFRES*RIGHT*~NESTENT    0.0611247  0.0207824   1
~BOUND*~LOCCON*~BENCOST*COLGOVE*USERMON*~SYSTMON*GRADSAN*CONFRES*RIGHT*~NESTENT    0.0812958  0.0409536   1
~BOUND*~LOCCON*~BENCOST*COLGOVE*~USERMON*SYSTMON*~GRADSAN*CONFRES*RIGHT*NESTENT    0.0611247  0.0409536   1

solution coverage: 0.838631
solution consistency: 1
```

7. Sensitivity analysis

Sensitivity analysis for fsQCA was done in two ways: 1) Analysis of complete cases only, and 2) Increase frequency cutoff to two cases instead of one in the truth table analysis. The results are presented in the following.

7.1 Analysis of complete cases (46 cases)

Necessary condition

Analysis of Necessary Conditions

Outcome variable: ROBUST

Conditions tested:

	Consistency	Coverage
BOUND	0.945233	0.977482
LOCCON	0.727813	0.915733
BENCOST	0.846255	0.827152
COLGOVE	0.836358	0.852961
USERMON	1.000000	0.842412
SYSTMON	0.956450	0.925607
GRADSAN	0.967008	0.871025
CONFRES	0.934015	0.725711
RIGHT	1.000000	0.857668
NESTENT	0.780600	0.855387

Analysis of Necessary Conditions

Outcome variable: ~ROBUST

Conditions tested:

	Consistency	Coverage
~BOUND	0.957935	0.900539
~LOCCON	0.870618	0.623460
~BENCOST	0.658381	0.689126
~COLGOVE	0.721479	0.695332
~USERMON	0.638623	1.000000
~SYSTMON	0.851498	0.910082
~GRADSAN	0.723391	0.919028
~CONFRES	0.318037	0.713877
~RIGHT	0.679414	1.000000
~NESTENT	0.745061	0.637405

The results of necessary condition analysis shows that BOUND, USERMON, SYSTMON, GRADSAN, CONFRES, and RIGHTORG are necessary for ROBUST outcome (see red box). This is different with the results showed in the analysis for all cases (missing case included), where GRADSAN and CONFRES are found unnecessary for the outcome. The result is expected considering that those two conditions were the source of missing data. However, the necessity of GRADSAN is questionable, since there are cases where graduated sanction is truly absent (0) but the evaluation of the outcome shows ROBUST. In addition, when we test the absence of conditions for the fail or un-success outcome, the result show only ~BOUND pass the consistency threshold of 0.9 which indicate that the absence of the condition is necessary for the ~ROBUST outcome, consistent with the result from the analysis for all cases.

Sufficient condition for ROBUST outcome

Parsimonious solution

```
*********************
*TRUTH TABLE ANALYSIS*
*********************

File:  //uofa/USERS$/users8/a1697278/Data/Ostrom paper/200224.csv
Model: ROBUST = f(BOUND, LOCCON, BENCOST, COLGOVE, USERMON, SYSTMON, GRADSAN, CONFRES, RIGHT, NESTENT)
Algorithm: Quine-McCluskey

--- PARSIMONIOUS SOLUTION ---
frequency cutoff: 1
consistency cutoff: 1
                              raw       unique
                            coverage    coverage    consistency
                           ----------  ----------  ----------
USERMON*SYSTMON            0.95645     0.2613      0.966978
LOCCON*SYSTMON*RIGHT       0.69515     0           1

solution coverage: 0.95645
solution consistency: 0.966978
```

Intermediate solution

```
*********************
*TRUTH TABLE ANALYSIS*
*********************

File:  //uofa/USERS$/users8/a1697278/Data/Ostrom paper/200224.csv
Model: ROBUST = f(BOUND, LOCCON, BENCOST, COLGOVE, USERMON, SYSTMON, GRADSAN, CONFRES, RIGHT, NESTENT)
Algorithm: Quine-McCluskey

--- INTERMEDIATE SOLUTION ---
frequency cutoff: 1
consistency cutoff: 1
Assumptions:
                                                                        raw       unique
                                                                      coverage    coverage    consistency
                                                                     ----------  ----------  ----------
BOUND*LOCCON*COLGOVE*USERMON*SYSTMON*GRADSAN*RIGHT*NESTENT           0.507753    0.0442099   1
BOUND*LOCCON*BENCOST*COLGOVE*USERMON*SYSTMON*CONFRES*RIGHT*~NESTENT  0.1323      0.110525    1
LOCCON*~BENCOST*COLGOVE*USERMON*SYSTMON*GRADSAN*CONFRES*RIGHT*NESTENT 0.120752   0.0112174   1
BOUND*LOCCON*BENCOST*USERMON*SYSTMON*GRADSAN*CONFRES*RIGHT*NESTENT   0.474101    0.0329924   1

solution coverage: 0.662488
solution consistency: 1
```

The results of truth table analysis shows that there are two minimum configurations for a robust outcome. The results are consistent with the results from the main analysis. For intermediate solution, the results show only four configurations of conditions sufficient to the robust outcome instead of seven as shown in the analysis of all cases. These configurations are the same with the configurations in the main analysis, i.e. path 1a, 1c, 1e, and 2b.

7.2 Sufficiency analysis for ~ROBUST outcome

Parsimonious solution

```
*********************
*TRUTH TABLE ANALYSIS*
*********************

File:  //uofa/USERS$/users8/a1697278/Data/Ostrom paper/200224.csv
Model: ~ROBUST = f(BOUND, LOCCON, BENCOST, COLGOVE, USERMON, SYSTMON, GRADSAN, CONFRES, RIGHT, NESTENT)
Algorithm: Quine-McCluskey

--- PARSIMONIOUS SOLUTION ---
frequency cutoff: 1
consistency cutoff: 1
                       raw       unique
                     coverage    coverage    consistency
                    ----------  ----------  ----------
~SYSTMON            0.851498    0.234544    0.910082
~BOUND*~GRADSAN     0.702358    0.0854048   1

solution coverage: 0.936903
solution consistency: 0.917603
```

Solution	Case
~SYSTMON	Bida(1,1), Bulgarian IS (1,1), Kuhl (1,1), Likii WRUA (1,0.67), MRIS KwaZulu-Natal (1,1), Nickerie (1,1), Qorir SSI (1,1), Saint Raphael (1,0.67), Wang village (1,0.67), Wen village (1,0.67), Western Mancha (1,1), Yaqut village (1,1), Gnangara (0.67,1), Lombok Subak (0.67,0.67), Mendoza (0.67,1), Quashini (0.67,0.67)
~BOUND*~GRADSAN	Bida(1,1), Bulgarian IS (1,1), Kuhl (1,1), Nickerie (1,1), Qorir SSI (1,1), Western Mancha (1,1), Yaqut village (1,1), Gnangara (0.67,1), JV WUAs (0.67,1), Mendoza (0.67,1), MRIS KwaZulu-Natal (0.67,1), Saint Raphael (0.67,0.67), Taita (0.67,0.67)

Intermediate solution

```
*********************
*TRUTH TABLE ANALYSIS*
*********************

File:  //uofa/USERS$/users8/a1697278/Data/Ostrom paper/200224.csv
Model: ~ROBUST = f(BOUND, LOCCON, BENCOST, COLGOVE, USERMON, SYSTMON, GRADSAN, CONFRES, RIGHT, NESTENT)
Algorithm: Quine-McCluskey

--- INTERMEDIATE SOLUTION ---
frequency cutoff: 1
consistency cutoff: 1
Assumptions:
                                                                                   raw       unique
                                                                                 coverage    coverage    consistency
                                                                                ----------  ----------  ----------
~BOUND*~LOCCON*~BENCOST*~COLGOVE*~USERMON*~SYSTMON*~GRADSAN*~RIGHT*~NESTENT       0.382409    0.191842    1
~BOUND*~LOCCON*~COLGOVE*~USERMON*~SYSTMON*~GRADSAN*CONFRES*~RIGHT*~NESTENT        0.233907    0.0433397   1
~BOUND*LOCCON*BENCOST*COLGOVE*USERMON*~SYSTMON*GRADSAN*CONFRES*RIGHT              0.170809    0.149777    1
~BOUND*~LOCCON*~BENCOST*COLGOVE*~USERMON*~SYSTMON*~GRADSAN*CONFRES*~RIGHT*NESTENT 0.0427024   0.0216699   1
~BOUND*~LOCCON*~BENCOST*~COLGOVE*~USERMON*~SYSTMON*~GRADSAN*CONFRES*RIGHT*NESTENT 0.0427024   0.0216699   1
~BOUND*LOCCON*BENCOST*~COLGOVE*~USERMON*SYSTMON*~GRADSAN*CONFRES*~RIGHT*~NESTENT  0.0427024   0.0427024   1
~BOUND*~LOCCON*BENCOST*COLGOVE*USERMON*~SYSTMON*~GRADSAN*CONFRES*RIGHT*~NESTENT   0.0427024   0.0216699   1
~BOUND*~LOCCON*~BENCOST*COLGOVE*USERMON*~SYSTMON*GRADSAN*CONFRES*RIGHT*~NESTENT   0.0847674   0.0427024   1
~BOUND*~LOCCON*~BENCOST*COLGOVE*~USERMON*SYSTMON*~GRADSAN*CONFRES*RIGHT*NESTENT   0.0637349   0.0427024   1

solution coverage: 0.83174
solution consistency: 1
```

Solutions	Case
~BOUND*~LOCCON*~BENCOST*~COLGOVE* ~USERMON*~SYSTMON*~GRADSAN* ~RIGHT*~NESTENT	Kuhl (1,1), Yaqut village (1,1), Gnangara (0.67,1), MRIS KwaZulu-Natal (0.67,1), Nickerie (0.67,1)
~BOUND*~LOCCON*~COLGOVE*~USERMON* ~SYSTMON*GRADSAN*CONFRES*~RIGHT*~NESTENT	Kuhl (1,1), QorirSSI (0.67,1), Gnangara (0.67,1), Western Mancha (0.67,1)
~BOUND*LOCCON*BENCOST*COLGOVE*USERMON* ~SYSTMON*GRADSAN*CONFRES*RIGHT	LikiiWRUA (0.67,0.67), Quashini (0.67,0.67), Wang village (0.67,0.67), Wen village (0.67,0.67)
~BOUND*~LOCCON*~BENCOST*COLGOVE*~USERMON* ~SYSTMON*~GRADSAN*CONFRES*~RIGHT*NESTENT	Bida (0.67,1)
~BOUND*~LOCCON*~BENCOST*~COLGOVE*~USERMON* ~SYSTMON*~GRADSAN*CONFRES*RIGHT*NESTENT	Mendoza (0.67,1)
~BOUND*LOCCON*BENCOST*~COLGOVE*~USERMON* SYSTMON*~GRADSAN*CONFRES*~RIGHT*~NESTENT	JVWUAs (0.67,1)
~BOUND*~LOCCON*BENCOST*COLGOVE*USERMON* ~SYSTMON*~GRADSAN*CONFRES*RIGHT*~NESTENT	Saint Raphael (0.67,0.67)
~BOUND*~LOCCON*~BENCOST*COLGOVE*USERMON* ~SYSTMON*GRADSAN*CONFRES*RIGHT*~NESTENT	Lombok Subak (0.67,0.67)
~BOUND*~LOCCON*~BENCOST*COLGOVE*~USERMON* SYSTMON*~GRADSAN*CONFRES*RIGHT*NESTENT	Taita (0.67,0.67)

7.3 Increasing frequency cutoff from 1 case to 2 cases in the outcome

Another way to test the robustness of the analysis is to increase the frequency cutoff (Skaaning 2011).

Frequency cutoff: 2 (for all cases; 41 cases included in the analysis after cutoff)

Parsimonious solution

```
*********************
*TRUTH TABLE ANALYSIS*
*********************

File:  //uofa/USERS$/users8/a1697278/Data/Ostrom paper/100419_62cases_fsQCA.csv
Model: ROBUST = f(BOUND, LOCCON, BENCOST, COLGOVE, USERMON, SYSTMON, GRADSAN, CONFRES, RIGHT, NESTENT)
Algorithm: Quine-McCluskey

--- PARSIMONIOUS SOLUTION ---
frequency cutoff: 2
consistency cutoff: 1
               raw       unique
             coverage   coverage   consistency
            ---------- ---------- ----------
BOUND       0.948948   0.0289221   0.98499
SYSTMON     0.971078   0.0510517   0.950054

solution coverage: 1
solution consistency: 0.951428


Cases with greater than 0.5 membership in term BOUND: Alicante (1,1),
  BadaSpateIrrigationsystem (1,1), BahrSeilaFayoum (1,1), BalineseSubak (1,1),
  BusaoCIS (1,1), ChaisombatMuangFai (1,1), ContemporarySubak (1,1),
  CulebraAsequias (1,1), EasternLaMancha (1,1), FalajAlKhatmeen (1,1),
  Ghayl (1,1), Ghaziqanat (1,1), Huaynacotas (1,1),
  KaryaMandiriIrrigationSystem (1,1), LaVegadeValencia (1,1), Madarounfairrigationsystem (1,1),
  Marakwetirrigationsystem (1,1), MasaiIrrigationSystem (1,1), Murcia&Orihuela (1,1),
  Nabagramirrigationsystem (1,1)
Cases with greater than 0.5 membership in term SYSTMON: Alicante (1,1),
  BadaSpateIrrigationsystem (1,1), BahrSeilaFayoum (1,1), BalineseSubak (1,1),
  BusaoCIS (1,1), ChaisombatMuangFai (1,1), ContemporarySubak (1,1),
  CulebraAsequias (1,1), EasternLaMancha (1,1), FalajAlKhatmeen (1,1),
  Ghayl (1,1), Ghaziqanat (1,1), Huaynacotas (1,1), |
  JVWUAs (1,0), KaryaMandiriIrrigationSystem (1,1), LaVegadeValencia (1,1),
  Madarounfairrigationsystem (1,1), Marakwetirrigationsystem (1,1), MasaiIrrigationSystem (1,1),
  Mkanyeni (1,1)
```

Intermediate solution

```
*********************
*TRUTH TABLE ANALYSIS*
*********************

File:  //uofa/USERS$/users8/a1697278/Data/Ostrom paper/100419_62cases_fsQCA.csv
Model: ROBUST = f(BOUND, LOCCON, BENCOST, COLGOVE, USERMON, SYSTMON, GRADSAN, CONFRES, RIGHT, NESTENT)
Algorithm: Quine-McCluskey

--- INTERMEDIATE SOLUTION ---
frequency cutoff: 2
consistency cutoff: 1
Assumptions:
                                                                          raw       unique
                                                                        coverage   coverage   consistency

                                                                       ---------- ---------- ----------
BOUND*LOCCON*BENCOST*COLGOVE*USERMON*SYSTMON*CONFRES*RIGHT           0.520158   0.0585013   1
BOUND*LOCCON*BENCOST*COLGOVE*USERMON*SYSTMON*GRADSAN*RIGHT*~NESTENT  0.117003   0.0438212   1
BOUND*LOCCON*BENCOST*COLGOVE*USERMON*SYSTMON*~GRADSAN*RIGHT*NESTENT  0.139351   0.0293602   1
BOUND*LOCCON*COLGOVE*USERMON*SYSTMON*GRADSAN*CONFRES*RIGHT*NESTENT   0.315074   0.0221297   1

solution coverage: 0.615469
solution consistency: 1
```

Case covered:

```
Cases with greater than 0.5 membership in term BOUND*LOCCON*BENCOST*COLGOVE*USERMON*SYSTMON*CONFRES*RIGHT: EasternLaMancha (1,1),
  Ghayl (1,1), Alicante (0.67,1), BalineseSubak (0.67,1),
  BusaoCIS (0.67,1), ChaisombatMuangFai (0.67,1), CulebraAsequias (0.67,1),
  FalajAlKhatmeen (0.67,1), Huaynacotas (0.67,1), KaryaMandiriIrrigationSystem (0.67,1),
  LaVegadeValencia (0.67,1), Madarounfairrigationsystem (0.67,1), MasaiIrrigationSystem (0.67,1),
  Murcia&Orihuela (0.67,1), Nabagramirrigationsystem (0.67,1), Nishikanbara (0.67,1),
  NortheasternColorado (0.67,1), ORIC (0.67,1), PongsakMuangFai (0.67,1),
  Porotog (0.67,1)
Cases with greater than 0.5 membership in term BOUND*LOCCON*BENCOST*COLGOVE*USERMON*SYSTMON*GRADSAN*RIGHT*~NESTENT: ThaloKulo (1,1),
  Huaynacotas (0.67,1), MasaiIrrigationSystem (0.67,1), ORIC (0.67,1),
  RajKulo (0.67,1), SangharLahrirrigationsystem (0.67,1)
Cases with greater than 0.5 membership in term BOUND*LOCCON*BENCOST*COLGOVE*USERMON*SYSTMON*~GRADSAN*RIGHT*NESTENT: FalajAlKhatmeen (0.67,1),
  Ghaziqanat (0.67,1), Nabagramirrigationsystem (0.67,1), Nishikanbara (0.67,1),
  NortheasternColorado (0.67,1), Shirgin (0.67,1), SidiOkba (0.67,1),
  Tharigatwatersed (0.67,1), ZanjeraDanum (0.67,1)
Cases with greater than 0.5 membership in term BOUND*LOCCON*COLGOVE*USERMON*SYSTMON*GRADSAN*CONFRES*RIGHT*NESTENT: EasternLaMancha (1,1),
  Valencia (1,1), Alicante (0.67,1), BadaSpateIrrigationsystem (0.67,1),
  BalineseSubak (0.67,1), BusaoCIS (0.67,1), ChaisombatMuangFai (0.67,1),
  CulebraAsequias (0.67,1), KaryaMandiriIrrigationSystem (0.67,1), LaVegadeValencia (0.67,1),
  Murcia&Orihuela (0.67,1), Porotog (0.67,1), SoprongMuangFai (0.67,1),
  TaiwanIA (0.67,1), TaosValley (0.67,1), TihinganSubak (0.67,1),
  TwyfordCooperative (0.67,1), UsosyUmbroCochabamba (0.67,1), UtahValley (0.67,1)
```

Frequency cutoff: 2 (compete case: 32 cases included in the analysis after cutoff)

Sufficiency analysis for complete case only. Because all outcome displayed 1 case is dropped from the analysis, out of 46 complete cases, only 32 cases included in the analysis.

```
**********************
*TRUTH TABLE ANALYSIS*
**********************

File:  //uofa/USERS$/users8/a1697278/Data/Ostrom paper/200224.csv
Model: ROBUST = f(BOUND, LOCCON, BENCOST, COLGOVE, USERMON, SYSTMON, GRADSAN, CONFRES, RIGTORG, NESTENT)
Algorithm: Quine-McCluskey

--- PARSIMONIOUS SOLUTION ---
frequency cutoff: 2
consistency cutoff: 1
               raw       unique
             coverage    coverage    consistency
            ----------  ----------  ----------
BOUND       0.945233    0.04355     0.977482
SYSTMON     0.95645     0.0547674   0.925607

solution coverage: 1
solution consistency: 0.928615


Cases with greater than 0.5 membership in term BOUND: Alicante (1,1),
  BadaSpateIrrigationsystem (1,1), BahrSeilaFayoum (1,1), BalineseSubak (1,1),
  BusaoCIS (1,1), ChaisombatMuangFai (1,1), ContemporarySubak (1,1),
  CulebraAsequias (1,1), EasternLaMancha (1,1), Huaynacotas (1,1),
  KaryaMandiriIrrigationSystem (1,1), LaVegadeValencia (1,1), Marakwetirrigationsystem (1,1),
  MasaiIrrigationSystem (1,1), Murcia&Orihuela (1,1), ORIC (1,1),
  PongsakMuangFai (1,1), Porotog (1,1), SangharLahrirrigationsystem (1,1),
  SoprongMuangFai (1,1)
Cases with greater than 0.5 membership in term SYSTMON: Alicante (1,1),
  BadaSpateIrrigationsystem (1,1), BahrSeilaFayoum (1,1), BalineseSubak (1,1),
  BusaoCIS (1,1), ChaisombatMuangFai (1,1), ContemporarySubak (1,1),
  CulebraAsequias (1,1), EasternLaMancha (1,1), Huaynacotas (1,1),
  JVWUAs (1,0), KaryaMandiriIrrigationSystem (1,1), LaVegadeValencia (1,1),
  Marakwetirrigationsystem (1,1), MasaiIrrigationSystem (1,1), Mkanyeni (1,1),
  Murcia&Orihuela (1,1), ORIC (1,1), PongsakMuangFai (1,1),
  Porotog (1,1)
```

Based on the above result, the minimum configuration for ROBUST outcome is now reduced to BOUND + SYSTMON, which reflect two of the necessary conditions that are more important than others based on the coverage (please refer to the necessary conditions for all cases).

The intermediate solution shows two configurations that lead to the ROBUST outcome, in which all the seven or eight design principles are included. However, the low coverage shows that there are substantial cases that cannot be represented by the two paths.

```
*********************
*TRUTH TABLE ANALYSIS*
*********************

File:  //uofa/USERS$/users8/a1697278/Data/Ostrom paper/200224.csv
Model: ROBUST = f(BOUND, LOCCON, BENCOST, COLGOVE, USERMON, SYSTMON, GRADSAN, CONFRES, RIGTORG, NESTENT)
Algorithm: Quine-McCluskey

--- INTERMEDIATE SOLUTION ---
frequency cutoff: 2
consistency cutoff: 1
Assumptions:
                                                                         raw       unique
                                                                       coverage   coverage    consistency
                                                                      ---------- ----------  ----------
BOUND*LOCCON*BENCOST*COLGOVE*USERMON*SYSTMON*GRADSAN*CONFRES*RIGTORG    0.529528   0.0884196   1
BOUND*LOCCON*COLGOVE*USERMON*SYSTMON*GRADSAN*CONFRES*RIGTORG*NESTENT    0.474431   0.0333223   1

solution coverage: 0.562851
solution consistency: 1


Cases with greater than 0.5 membership in term BOUND*LOCCON*BENCOST*COLGOVE*USERMON*SYSTMON*GRADSAN*CONFRES*RIGTORG: EasternLaMancha (1,1),
  Alicante (0.67,1), BalineseSubak (0.67,1), BusaoCIS (0.67,1),
  ChaisombatMuangFai (0.67,1), CulebraAsequias (0.67,1), Huaynacotas (0.67,1),
  KaryaMandiriIrrigationSystem (0.67,1), LaVegadeValencia (0.67,1), MasaiIrrigationSystem (0.67,1),
  Murcia&Orihuela (0.67,1), ORIC (0.67,1), Porotog (0.67,1),
  SangharLahrirrigationsystem (0.67,1), SoprongMuangFai (0.67,1), TaiwanIA (0.67,1),
  TaosValley (0.67,1), TihinganSubak (0.67,1), TwyfordCooperative (0.67,1),
  UsosyUmbroCochabamba (0.67,1)
Cases with greater than 0.5 membership in term BOUND*LOCCON*COLGOVE*USERMON*SYSTMON*GRADSAN*CONFRES*RIGTORG*NESTENT: EasternLaMancha (1,1),
  Valencia (1,1), Alicante (0.67,1), BadaSpateIrrigationsystem (0.67,1),
  BalineseSubak (0.67,1), BusaoCIS (0.67,1), ChaisombatMuangFai (0.67,1),
  CulebraAsequias (0.67,1), KaryaMandiriIrrigationSystem (0.67,1), LaVegadeValencia (0.67,1),
  Murcia&Orihuela (0.67,1), Porotog (0.67,1), SoprongMuangFai (0.67,1),
  TaiwanIA (0.67,1), TaosValley (0.67,1), TihinganSubak (0.67,1),
  TwyfordCooperative (0.67,1), UsosyUmbroCochabamba (0.67,1), UtahValley (0.67,1)
```

Parsimonious solution for ~ROBUST outcome

```
*********************
*TRUTH TABLE ANALYSIS*
*********************

File:  //uofa/USERS$/users8/a1697278/Data/Ostrom paper/100419_62cases_fsQCA.csv
Model: ~ROBUST = f(BOUND, LOCCON, BENCOST, COLGOVE, USERMON, SYSTMON, GRADSAN, CONFRES, RIGHT, NESTENT)
Algorithm: Quine-McCluskey

--- PARSIMONIOUS SOLUTION ---
frequency cutoff: 2
consistency cutoff: 1
               raw       unique
             coverage   coverage    consistency
            ---------- ----------  ----------
~SYSTMON     0.857579   0           0.914007
~BOUND       0.959658   0.102078    0.870771

solution coverage: 0.959658
solution consistency: 0.81137
```

Case covered:

```
Cases with greater than 0.5 membership in term ~SYSTMON: BidaIrrigationsystem (1,1),
  Bulgarianirrigationsystem (1,1), KuhlIrrigationSystem (1,1), LikiiWRUA (1,0.67),
  MRISKwaZulu-Natal (1,1), Nickerieirrigation (1,1), QorirSSI (1,1),
  SaintRaphaelirrigationsystem (1,0.67), Wangvillageirrigation (1,0.67), Wenvillageirrigationsystem (1,0.67),
  WesternMancha (1,1), Yaqutvillage (1,1), Gnangara (0.67,1),
  LombokSubak (0.67,0.67), Mendoza (0.67,1), NorthAfghanirrigation (0.67,0.67),
  QuashiniIrrigationSystem (0.67,0.67)
Cases with greater than 0.5 membership in term ~BOUND: BidaIrrigationsystem (1,1),
  Bulgarianirrigationsystem (1,1), Gnangara (1,1), KuhlIrrigationSystem (1,1),
  LombokSubak (1,0.67), MRISKwaZulu-Natal (1,1), Nickerieirrigation (1,1),
  QorirSSI (1,1), QuashiniIrrigationSystem (1,0.67), TaitaIrrigationsystem (1,0.67),
  WesternMancha (1,1), Yaqutvillage (1,1), JVWUAs (0.67,1),
  LikiiWRUA (0.67,0.67), Mendoza (0.67,1), Mkanyeni (0.67,0),
  NorthAfghanirrigation (0.67,0.67), NsharaFurrow (0.67,0), SaintRaphaelirrigationsystem (0.67,0.67),
  Wangvillageirrigation (0.67,0.67)
```

Intermediate solution for ~ROBUST outcome

```
*********************
*TRUTH TABLE ANALYSIS*
*********************

File:  //uofa/USERS$/users8/a1697278/Data/Ostrom paper/200224.csv
Model: ~ROBUST = f(BOUND, LOCCON, BENCOST, COLGOVE, USERMON, SYSTMON, GRADSAN, CONFRES, RIGTORG, NESTENT)
Algorithm: Quine-McCluskey

--- INTERMEDIATE SOLUTION ---
frequency cutoff: 2
consistency cutoff: 1
Assumptions:
                                                                                  raw       unique
                                                                                coverage   coverage   consistency
                                                                               ---------- ----------  ----------
~BOUND*~LOCCON*~BENCOST*~COLGOVE*~USERMON*~SYSTMON*~GRADSAN*~RIGTORG*~NESTENT   0.382409   0.191842    1
~BOUND*~LOCCON*~COLGOVE*~USERMON*~SYSTMON*~GRADSAN*CONFRES*~RIGTORG*~NESTENT    0.233907   0.0433397   1
~BOUND*LOCCON*BENCOST*COLGOVE*USERMON*~SYSTMON*GRADSAN*CONFRES*RIGTORG*~NESTENT 0.128107   0.128107    1

solution coverage: 0.553856
solution consistency: 1

|
Cases with greater than 0.5 membership in term ~BOUND*~LOCCON*~BENCOST*~COLGOVE*~USERMON*~SYSTMON*~GRADSAN*~RIGTORG*~NESTENT: Bulgarianirrigationsystem (1,1),
  KuhlIrrigationSystem (1,1), Yaqutvillage (1,1), Gnangara (0.67,1),
  MRISKwaZulu-Natal (0.67,1), Nickerieirrigation (0.67,1)
Cases with greater than 0.5 membership in term ~BOUND*~LOCCON*~COLGOVE*~USERMON*~SYSTMON*~GRADSAN*CONFRES*~RIGTORG*~NESTENT: KuhlIrrigationSystem (1,1),
  QorirSSI (0.67,1), Gnangara (0.67,1), WesternMancha (0.67,1)
Cases with greater than 0.5 membership in term ~BOUND*LOCCON*BENCOST*COLGOVE*USERMON*~SYSTMON*GRADSAN*CONFRES*RIGTORG*~NESTENT: QuashiniIrrigationSystem (0.67,0.67),
  Wangvillageirrigation (0.67,0.67), Wenvillageirrigationsystem (0.67,0.67)
```

8. List of case studies

8.1. Case study for the meta-analysis

Table 9. List of case studies for meta-analysis.

No.	Case Identification	Country	Source / Author
1	Alicante	Spain	(Maass & Anderson 1978a)
2	Bada Spate Irrigation system	Eritrea	(Ghebremariam & van Steenbergen 2007)
3	Bahr Seila Fayoum	Egypt	(De Veer et al. 1993)
4	Balinese Subak (old)	Indonesia	(Birkelbach 1973)
5	Bida Irrigation system	Nigeria	(Fu et al. 2010)
6	Bulgarian irrigation system	Bulgaria	(Theesfeld 2004)
7	Busao CIS	The Philippines	(KAKUTA 2017)
8	Chaisombat Muang Fai	Thailand	(Ounvichit 2011)
9	Contemporary Subak	Indonesia	(Yekti et al. 2017)
10	Culebra Asequias	USA	(Hicks & Peña 2003)
11	Eastern La Mancha	Spain	(Esteban & Albiac 2012; Lopez-Gunn 2003)
12	Falaj Al-Khatmeen	Oman	(Al-Marshoudi 2018; Al-Marshudi 2007; Megdiche-Kharrat, Moussa & Rejeb 2017)
13	Ghayl	Yemen	(Varisco 1983)
14	Ghazi qanat	Iran	(Jomehpour 2009)
15	Gnangara	Australia	(Skurray 2015)
16	Huaynacotas, Peru	Peru	(Trawick 2001a, 2008; Trawick 2001b)
17	Jordan Valley	Jordan	(Altz-Stamm 2016; Molle, Venot & Hassan 2008; Mustafa, Altz-Stamm & Scott 2016)
18	Karya Mandiri	Indonesia	(Helmi 2017)
19	Kuhl Irrigation	Pakistan	(Sharma, Sharma & Prakash 2015)
20	La Vega de Valencia (new)	Spain	(Ortega-Reig et al. 2014)
21	Likii WRUA	Kenya	(Dell'Angelo et al. 2016)
22	Lombok Subak	Indonesia	(Sjah & Baldwin 2014)
23	Madarounfa	Niger	(Norman 1997)
24	Marakwet	Kenya	(Adams, Watson & Mutiso 1997)
25	Masai	Tanzania	(Caretta 2015)
26	Mendoza	Argentina	(Chambouleyron 1989; Díaz Araujo & Bertranou 2004; Hurlbert & Mussetta 2016)
27	Mkanyeni Furrow	Tanzania	(Komakech, Van Der Zaag & Van Koppen 2012)
28	MRIS KwaZulu-Natal	South Africa	(Muchara 2014)
29	Murcia & Orihuela	Spain	(Maass & Anderson 1978c)
30	Nabagram	Bangladesh	(Coward Jr & Ahmed 1979)
31	Nickerie	Suriname	(Núñez & Colmenero 2013)
32	Nishikanbara	Japan	(Sarker 2013; Sarker et al. 2014)

33	North Afghan irrigation	Afghanistan	(Abdullaev & Shah 2011; Thomas & Ahmad 2009)
34	Northeastern Colorado	USA	(Maass & Anderson 1978d)
35	Nshara Furrow	Tanzania	(Gillingham 1999)
36	ORIC	Zimbabwe	(Senzanje & Van der Zaag 2004)
37	Pongsak Muang Fai	Thailand	(Ounvichit et al. 2006)
38	Porotog	Ecuador	(Communal et al. 2016; Hoogesteger 2013; Perreault, Bebbington & Carroll 1998)
39	Qorir SSI	Ethiopia	(Habtamu 2011)
40	Quashini	Ethiopia	(Belay & Bewket 2013)
41	Raj Kulo	Nepal	(Martin & Yoder 1988)
42	Saint Raphael	Haiti	(Boyer, Speelman & Van Huylenbroeck 2011)
43	Sanghar Lahr	Pakistan	(Kamran & Shivakoti 2013a, 2013b)
44	Shirgin	Tajikistan	(Dörre & Goibnazarov 2018)
45	Sidi Okba	Algeria	(Hamamouche et al. 2017)
46	Soprong Muang Fai	Thailand	(Ounvichit, Wattayu & Satoh 2008)
47	Taita	Kenya	(Fleuret 1985)
48	Taiwan IA	Taiwan	(Lam 1996)
49	Taos Valley	USA	(Cox 2014; Cox & Ross 2011)
50	Thalo Kulo	Nepal	(Martin & Yoder 1988)
51	Tharigat watersed	India	(Satyal, Kumar & Kandpal 2006)
52	Tihingan Subak	Indonesia	(Geertz 1964)
53	Twyford Cooperative	New Zealand	(Boone & Fragaszy 2018)
54	Usos y costumbres Cochabamba	Bolivia	(Perreault 2008)
55	Utah Valley	USA	(Maass & Anderson 1978e)
56	Valencia (old)	Spain	(Glick 1970; Maass & Anderson 1978b)
57	Wadi Laba	Eritrea	(Mehari, Schultz & Depeweg 2005)
58	Wang village irrigation	China	(Yu 2016; Yu et al. 2016)
59	Wen village irrigation system	China	(Yu 2016; Yu et al. 2016)
60	Western Mancha	Spain	(Esteban & Albiac 2012; Lopez-Gunn 2003)
61	Yaqut village	Egypt	(Radwan 1997)
62	Zanjera Danum	The Philippines	(Coward Jr 1979)

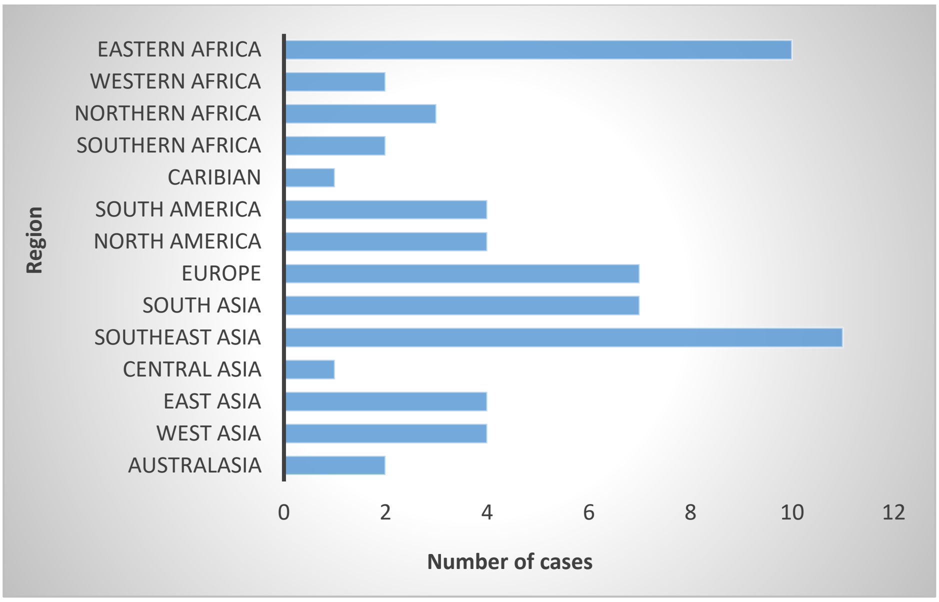

Figure 1. Distribution of 62 cases by region

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Appendix 4. Human Research Ethic Approval

THE UNIVERSITY *of* ADELAIDE

RESEARCH SERVICES
OFFICE OF RESEARCH ETHICS, COMPLIANCE AND INTEGRITY
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8 August 2017

Professor M Young
Centre for Global Food and Resources

Dear Professor Young

ETHICS APPROVAL No: H-2017-139

PROJECT TITLE: Improving the robustness of water management in Indonesia

The ethics application for the above project has been reviewed by the Low Risk Human Research Ethics Review Group (Faculty of Arts and Faculty of the Professions) and is deemed to meet the requirements of the *National Statement on Ethical Conduct in Human Research (2007)* involving no more than low risk for research participants. You are authorised to commence your research on **08 Aug 2017**.

Ethics approval is granted for three years and is subject to satisfactory annual reporting. The form titled *Annual Report on Project Status* is to be used when reporting annual progress and project completion and can be downloaded at http://www.adelaide.edu.au/research-services/oreci/human/reporting/. Prior to expiry, ethics approval may be extended for a further period.

Participants in the study are to be given a copy of the Information Sheet and the signed Consent Form to retain. It is also a condition of approval that you **immediately report** anything which might warrant review of ethical approval including:

- serious or unexpected adverse effects on participants,
- previously unforeseen events which might affect continued ethical acceptability of the project,
- proposed changes to the protocol; and
- the project is discontinued before the expected date of completion.

Please refer to the following ethics approval document for any additional conditions that may apply to this project.

Yours sincerely

DR JOHN TIBBY
Co-Convenor
Low Risk Human Research Ethics Review Group
(Faculty of Arts and Faculty of the Professions)

DR JOANNA HOWE
Co-Convenor
Low Risk Human Research Ethics Review Group
(Faculty of Arts and Faculty of the Professions)