Commons Governance for Robust Systems: Irrigation Systems Study Under a Multi-Method Approach

by

Cathy Rubinos

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Graduate Supervisory Committee:

John M. Anderies, Chair
Joshua Abbott
Marcus A. Janssen

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ABSTRACT

Sustainability depends in part on our capacity to resolve dilemmas of the commons in Coupled Infrastructure Systems (CIS). Thus, we need to know more about how to incentivize individuals to take collective action to manage shared resources. Moreover, given that we will experience new and more extreme weather events due to climate change, we need to learn how to increase the robustness of CIS to those shocks. This dissertation studies irrigation systems to contribute to the development of an empirically based theory of commons governance for robust systems. I first studied the eight institutional design principles (DPs) for long enduring systems of shared resources that the Nobel Prize winner Elinor Ostrom proposed in 1990. I performed a critical literature review of 64 studies that looked at the institutional configuration of CIS, and based on my findings I propose some modifications of their definitions and application in research and policy making. I then studied how the revisited design principles, when analyzed conjointly with biophysical and ethnographic characteristics of CISs, perform to avoid over-appropriation, poverty and critical conflicts among users of an irrigation system. After carrying out a meta-analysis of 28 cases around the world, I found that particular combinations of those variables related to population size, countries corruption, the condition of water storage, monitoring of users behavior, and involving users in the decision making process for the commons governance, were sufficient to obtain the desired outcomes. The two last studies were based on the Peruvian Piura Basin, a CIS that has been exposed to environmental shocks for decades. I used secondary and primary data to carry out a longitudinal study using as guidance the robustness framework, and different hypothesis from prominent collapse theories to draw potential explanations. I

then developed a dynamic model that shows how at the current situation it is more effective to invest in rules enforcement than in the improvement of the physical infrastructure (e.g. reservoir). Finally, I explored different strategies to increase the robustness of the system, through enabling collective action in the Basin.

DEDICATION

To Sofía

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CHAPTER 1

INTRODUCTION

Sustainability depends in part on our capacity to resolve dilemmas of the commons in Coupled Infrastructure Systems (CISs) (Anderies, 2015).[1] To be able to resolve those dilemmas, we need to know more about how to incentivize individuals to take collective action to manage shared resources (Janssen & Anderies, 2013). Empirical studies have shown that some communities organize themselves effectively to attain desirable outcomes, while other communities face resource over-appropriation and/or critical conflicts that they are unable to resolve (Cox et al., 2010; Winters et al., 2000; Ostrom, 1990; Poteete & Ostrom, 2004; Poteete et al., 2010; Schlager & Ostrom, 1992).

Elinor Ostrom's Nobel-Prize-winning work on the characteristics, management, and outcomes of common-pool resource governance has not only increased our understanding of what makes collective action successful or not, it also provides rich grounds for asking many more questions about what contributes to these different outcomes. In **Chapter 2**, I studied the eight design principles (DPs) for long enduring systems of shared resources that Ostrom (1990) noticed. I addressed the question: "What considerations should we have when using the design principles for theory building and/or policy making in order to obtain clarity and comprehensiveness?" by performing an analytical literature review of 64 studies that analyzed Ostrom's design principles in real world case studies, and others that did not explicitly mention the design principle but

[1] Coupled Infrastructure Systems (CIS) refers to Socio Ecological Systems (SES), but in CISs the joint causation by the different components (or Infrastructures) of a system is explicit. For a more detailed explanation, read Anderies (2015).

that included an institutional analysis on their study. I looked for clarity of each DP, for desired outcomes intended by each DP, and for circumstances found in the field or in research that suggest a direction for the refinement of the DPs.

For the following chapters, I focused on irrigation systems (a kind of CIS on which much data is available) to contribute to the development of an empirically based theory of commons governance. I chose to study irrigation systems because they are pure cases of shared resources: there is clear presence of resource appropriation, a public-infrastructure provisioning dilemma, and a relationship between the two phenomena. Other CISs such as forests, fisheries, and rangelands are particular cases of the general one represented by irrigation systems (Janssen & Anderies, 2013). Because my results are from pure cases of shared resources, they may be useful in generalizing about patterns in other CISs, and for informing theories of CIS governance. Moreover, the study of irrigation systems is timely given the anticipated impacts of climate change on freshwater availability, and given that agriculture, the main sector in terms of water use (70% of total global freshwater supply), will be one of the sectors most adversely affected by climate change (Cifdaloz, Regmi, Anderies & Rodriguez, 2010).

In **Chapter 3**, I leverage findings of chapter 2, and addressed the question: Given the biophysical and ethnographic characteristics (typologies) of a CIS, which institutions are necessary and/or sufficient to avoid over-appropriation, poverty and critical conflicts among users of an irrigation system? I performed a meta-analysis of 28 cases around the world, using qualitative comparative analysis (QCA) to find conjoint causation of different contextual variables (biophysical and ethnographic characteristics), and institutional variables (design principles) as conditions that cause a desired outcome (an indicator of levels of over-appropriation, poverty and conflicts in the system).

Chapters 4 and **5** are focused on the contribution on theory building for Robustness of CIS to environmental threats. In both chapters, using two different methods, I studied the Peruvian Piura Basin, a CIS that has been exposed to environmental shocks for decades. For **Chapter 4**, I used secondary and primary data to carry out a longitudinal study and address the question: How did the Piura Basin react to El Niño disturbances of 1982/1983 and 1997/1998, why did it react the way it did, and how are actors in the system preparing themselves for future events to come? I explore different hypothesis from prominent collapse theories to draw potential explanations. In **Chapter 5**, I developed a dynamic model to 1) understand the core dynamics of the systems with respect to the relationship between public-infrastructure and collective action, 2) to understand how robust the irrigation systems is to extreme flood events, and 3) to explore potential interventions to increase the robustness of these systems to flood events. Finally, in **Chapter 6,** I synthesize the research findings and discuss their theoretical and practical implications.

CHAPTER 2

A CRITICAL REVIEW OF OSTROM'S INSTITUTIONAL DESIGN PRINCIPLES AND A THEORY BUILDING AGENDA FOR SHARED RESOURCES MANAGEMENT

Introduction

When Elinor Ostrom, in "*Governing the Commons*" (1990) brought evidence to disprove the conventional wisdom that suggested that top-down governance, either by private companies or by the State, was the only way to avoid a tragedy of common goods, she unarguably enhanced our understanding of common pool resource (CPR) governance in socio-ecological systems (SES). Ostrom (1990) shared eight design principles (DPs) for long enduring systems of shared resources, and outlined how complex SES need context-specific propositions. This claim included the need for more empirically based research to observe commonalities at different layers of analysis and for different types of variables (biophysical, cultural/social and institutional) that foster sustainable CPR governance.

As an excellent scientist, Ostrom knew that she could not be sure that she had found the core set of principles, and she laid out her findings so other scholars could challenge them. *In a 2008,* in a conference article *"Design Principles of Robust Property Rights Institutions: What Have We Learned?"* Ostrom suggested rephrasing and expanding some of the original design principles based on some articles that studied the design principles on different case studies, in order to clarify them. However, she called again for the analysis of additional studies for its further refinement.

Since the publication of *Governing the Commons*, many authors have evaluated the management performance of different sets of real world CPRs, which purposely or not, reflect the presence of the design principles. Keeping in mind that Ostrom's analysis was on small-scale self-governing CPRs the challenge has been not only to test Ostrom's findings in small community-based systems, but also to look for their application and usefulness in different types of SES. Since every system contains a self-organizing component (Anderies, 2015), the applicability of the DPs to different SES remains strong.

Some studies have focused on single cases, and some have applied the analysis to a larger sample set (Cox et al. 2010, and Baggio et al., 2016). Some authors have studied the applicability of the principles to large-scale cases (Pomeroy et al. 2001, Young 2002, Berkes 2005, 2006), even to the global commons (Stern, 2011, Young 1997, 1999, Dietz et al., 2003, Epstein et al. 2014).

Table 2.1 reflects the variability of the types of research on the performance of design principles that we have identified and used for the analysis in this paper. To date, we have not found a single study that challenges the validity of the DPs. However, given the DPs lack of precision and that they are not considered a theory, they are not falsifiable, and vice versa (Popper, 1963). The immediate question is then, how are the DPs useful for theory building? Popperian science philosophers argue that the mediation of auxiliary assumptions often protects theories from direct falsification (Forster, 2000), which may have been the case of conventional CPR management theories before Ostrom's finding that context (in this case, a long list of auxiliary assumptions) matters. Given that the DPs are a logical, well-organized bundle of aspects shown to be relevant for governance, we believe that the DPs may be the unifiers of context and theory prediction. In other words, we believe that the DPs can help us answer in which context a CPR existing or future theory may be accurate at predicting outcomes, which is very much needed for SES governance. To get to this point, however, the DPs need a refinement, as Ostrom anticipated and as many authors suggest, to also be able to expand them to more complex CPRs and contemporary governance challenges.

Table 2.1

Type Of Research On The Performance Of Design Principles

N of Studies	Authors	Method
17	Araral, E. (2013), Berkes, F. (2002), Cleaver, F. D., & Franks, T. R. (2005), Cousins, B. (2000), Cox, M., & Ross, J. M. (2011), Epstein, G., Pérez, I., Schoon, M., & Meek, C. (2014), Gibson, C. C. (2001), Gonzalez-Aubone, F., Miranda, O., Montenegro, F., & Andrieu, J. (2014), Lam, W. F. (1996), McPartlon, E. (2016), Morrow, C. E., & Hull, R. W. (1996), Nilsson, T. (2001), Sarker, A., & Itoh, T. (2001), Steins, N. A & Edwards, V. M (1999), Trawick, P. B. (2001), Vogt, N. D., Banana, A., Gombya-Ssembajjwe, W., & Bahati, J. (2005) & Stern, P. (2011).	1 Case Study
6	Boyer, M., Speelman, S., & Van Huylenbroeck, G. (2011), Fleischman, F., Ban, N., Evans, L., Epstein, G., Garcia-Lopez, G., & Villamayor-Tomas, S. (2014), Garrido, S. (2011), Gautam, A. P., & Shivakoti, G. P. (2005), Huntjens, P., Lebel, L., Pahl-Wostl, C., Camkin, J., Schulze, R., & Kranz, N. (2012), Ross, A., & Martinez-Santos, P. (2008),	Comparative Case Study (Between 2 and 5 cases)
4	Agrawal, A. (2014), Berkes, F. (2005). Berkes, F. (2006), Dietz, T., Ostrom, E., & Stern, P. C. (2003)	Analytical Review of Literature of Empirical Cases
4	Lam, W. F. (1998), Tang, S. Y. (1992), Quinn, C. H., Huby, M., Kiwasila, H., & Lovett, J. C. (2007), Cox, M., Arnold, G., & Tomás, S. V. (2010),	Statistical Comparative Case Analysis (Between 38 and 150 cases)
1	Baggio, J., Barnett, A., Perez-Ibarra, I., Brady, U., Ratajczyk, E., Rollins, N., ... & Anderies, J. (2016).	Qualitative Comparative Analysis
1	Agrawal, A. (2002)	Qualitative Analysis of Meta-Analysis

We analyze individual and common research findings of the applicability of the design principles in real world CPRs. We share which are the common challenges that researchers had when studying the DPs, what are the main critiques and gaps that we need to address, and finally we share some thoughts and suggestions in order to offer a concise, but comprehensive compendium of the knowledge of design principles, and how they can be expanded to other CPRs governance systems, so it can be used and improved by scholars and practitioners interested in analyzing the design principles in different settings, either for CPR theory development, or for practical commons governance.

Method

We did a literature review of 64 studies that analyzed Ostrom's design principles in real world case studies, and others that did not explicitly mention the design principle but that included an institutional analysis on their study (see table 2.2). We are aware of the confirmatory bias challenge discussed by Araral (2014) and Cox et al. (2016), with regard to the inclination of authors that study DPs on real cases to confirm Ostrom's claim. The exercise done on this research is not to validate the DPs, since as we mentioned before we find this impossible from a logical and philosophical point of view; on the contrary, it includes the suggestions of those authors that found that some DPs should be modified, which also suggests that their analyses were critical of the DP, which is what we are looking for to advance our theory.

Table 2.2

Studies Included in the Analysis

No	***Reference***	***Method***	***N of cases***	***Design Principles Analysis***	***Type of Research***
1	Agrawal, A. (2002). Common resources and institutional sustainability. The drama of the commons, 41-85.	Qualitative Comparative Analysis of Meta-Analysis	3 Meta-Analysis. Wade (1988) 31 Villages, Ostrom (14 cases), Baland and Platteau	Partially	Book Chapter
2	Agrawal, A. (2014). Studying the commons, governing common-pool resource outcomes: Some concluding thoughts. Environmental Science & Policy, 36, 86-91.	Analytical Review of Literature	--	Yes	Journal Article
3	Araral, E. (2013). What makes socio-ecological systems robust? An institutional analysis of the 2,000 year-old Ifugao society. Human Ecology, 41(6), 859-870.	1 case Study	1	Yes	Journal Article
4	Baggio, J., Barnett, A., Perez-Ibarra, I., Brady, U., Ratajczyk, E., Rollins, N., ... & Anderies, J. (2016). Explaining success and failure in the commons: the configural nature of Ostrom's institutional design principles. International Journal of the Commons, 10(2).	Qualitative Comparative Analysis	69	Yes	Journal Article
5	Bardhan, P. (2000). Irrigation and cooperation: An empirical analysis of 48 irrigation communities in South India. Economic Development and cultural change, 48(4), 847-865.	Quantitative	48	No	Report
6	Berkes, F. (2002). Cross-scale institutional linkages: perspectives from the bottom up. The drama of the commons, 293-321.	1 case Study	1	Partially	Book Chapter
7	Berkes, F. (2005). Commons theory for marine resource management in a complex world. Senri Ethnological Studies, 67, 13-31.	Analytical Review of Literature	--	Yes	Article
8	Berkes, F. (2006). From community-based resource management to complex systems: the scale issue and marine commons. Ecology and Society, 11(1).	Analytical Review of Literature	4	Partially	Journal Article
9	Berry, S. (1993). No condition is permanent: The social dynamics of agrarian change in sub-Saharan Africa. University of Wisconsin Pres.	1 case Study	1	No	Research Paper
10	Berry, S. (1994). Resource access and management as historical processes-conceptual and methodological issues. Occasional Paper, (13). International Development Studies, Roskide University, Roskilde, 24-45.	1 case Study	1	No	Book Chapter
11	Boyer, M., Speelman, S., & Van Huylenbroeck, G. (2011). Institutional analysis of irrigation management in Haiti: a case study of three farmer managed schemes. Water Policy, 13(4), 555-570.	Comparative Case Study	3	Yes	Journal Article
12	Brewer, J. D., Sakthivadivel, R., & Raju, K. V. (1997). Water distribution rules and water distribution performance: a case study in the Tambraparani irrigation system (Vol. 12). IWMI.	1 case Study	1	No	Report

13	Chakraborty, R. N. (2004). Sharing rules and the commons: Evidence from Ha'apai, Tonga. Environment and Development Economics, 9(4), 455-472.	1 Case Study. Qualitative and Quantitative	1	No	Journal Article
14	Cinner, J., & McClanahan, T. R. (2006). Socioeconomic factors that lead to overfishing in small-scale coral reef fisheries of Papua New Guinea. Environmental Conservation, 33(1), 73-80.	1 Case Study	1	No	Journal Article
15	Cleaver, F. D., & Franks, T. R. (2005). How institutions elude design: river basin management and sustainable livelihoods.	1 case Study	1	Yes	Research Paper
16	Cousins, B. (2000). Tenure and common property resources in Africa. Evolving land rights, policy and tenure in Africa., 151-180.	1 case Study	1	Partially	Book Chapter
17	Cox, M., Arnold, G., & Tomás, S. V. (2010). A review of design principles for community-based natural resource management. Ecology and Society 15(4): 38.	Statistical Analysis	91	Yes	Journal Article
18	Cox, M., & Ross, J. M. (2011). Robustness and vulnerability of community irrigation systems: The case of the Taos valley acequias. Journal of Environmental Economics and Management, 61(3), 254-266.	1 case Study	1	Yes	Journal Article
19	Deribe, R. (2008). Institutional Analysis Of Water Management On Communal Irrigation Systems: The Case Of Atsbi Wemberta District In Tigray Region And Ada'a District In Oromiya Region, Ethiopia (Doctoral dissertation, Addis Ababa University).	Comparative Case Study	2	No	Thesis
20	Dietz, T., Ostrom, E., & Stern, P. C. (2003). The struggle to govern the commons. science, 302(5652), 1907-1912.	Theoretic Review	--	Yes	Journal Article
21	Downing, T. E. (1974). Irrigation and moisture-sensitive periods: A Zapotec case. University of Arizona Press,Tucson, AZ, USA. Chapter 10: 113-122.	1 case Study	1	No	Book Chapter
22	Epstein, G., Pérez, I., Schoon, M., & Meek, C. (2014). Governing the invisible commons: Ozone regulation and the Montreal Protocol. International Journal of the Commons, 8(2).	1 case Study	1	Yes	Journal Article
23	Fleischman, F., Ban, N., Evans, L., Epstein, G., Garcia-Lopez, G., & Villamayor-Tomas, S. (2014). Governing large-scale social-ecological systems: lessons from five cases. International Journal of the Commons, 8(2).	Comparative Case Study	5	Yes	Journal Article
24	Garrido, S. (2011). Las instituciones de riego en la España del este. Una reflexión a la luz de la obra de Elinor Ostrom.	Comparative Case Study	4	Yes	Research Paper
25	Gautam, A. P., & Shivakoti, G. P. (2005). Conditions for successful local collective action in forestry: some evidence from the hills of Nepal. Society and Natural Resources, 18(2), 153-171.	Comparative Case Study	2	Yes	Journal Article
26	Ghazouani, W., Molle, F., Swelam, A., Rap, E., & Abdo, A. (2015). Understanding farmers' adaptation to water scarcity: a case study from the western Nile Delta, Egypt (Vol. 160). IWMI.	1 case Study	1	No	Report
27	Gibson, C. C. (2001). Forest resources: Institutions for local governance in Guatemala. Protecting the commons: A framework for resource management in the Americas, 71-89.	1 case Study	1	Yes	Book Chapter
28	Gibson, C. C., Williams, J. T., & Ostrom, E. (2005). Local enforcement and better forests. World Development, 33(2), 273-284.	Qualitative and Quantitative	138 groups	No	Journal Article

29	Gonzalez-Aubone, F., Miranda, O., Montenegro, F., & Andrieu, J. (2014). Analizando la modernizacion en regadios tradicionales del oeste argentino. / Gestion del agua para riego de uso comun (RUC): la busqueda de un desempeno eficiente y sostenible a traves de un enfoque institucinoal. El caso de la provincia de San Juan, Argentina	1 case Study	1	Yes	Research Paper
30	Hayes, T., & Ostrom, E. (2005). Conserving the world's forests: Are protected areas the only way. Ind. L. Rev., 38, 595.	Qualitative with descriptive statistics	178 groups	No	Research Paper
31	Huntjens, P., Lebel, L., Pahl-Wostl, C., Camkin, J., Schulze, R., & Kranz, N. (2012). Institutional design propositions for the governance of adaptation to climate change in the water sector. Global Environmental Change, 22(1), 67-81.	Comparative Case Study	3	Yes	Journal Article
32	Lam, W. F. (1996). Institutional design of public agencies and coproduction: a study of irrigation associations in Taiwan. World development, 24(6), 1039-1054.	1 case Study	1	Yes	Journal Article
33	Lam, W. F. (1998). Governing irrigation systems in Nepal: institutions, infrastructure, and collective action. Institute for Contemporary Studies.	Comparative Case Study	150 systems	Yes	Book
34	Libecap, G. D. (1994). 7. The Conditions for Successful Collective Action. Journal of Theoretical Politics, 6(4), 563-592.	Comparative Case Study	3	No	Journal Article
35	López Gunn, E., & Hernández, N. (2001). La gestión colectiva de las aguas subterráneas en La Mancha: análisis comparativo. La economía del agua subterránea y su gestión colectiva, 405-473.	Comparative Case Study	2	No	Book Chapter
36	Lorenzen, S., & Lorenzen, R. P. (2005, August). A case study of Balinese irrigation management: institutional dynamics and challenges. In Second Southeast Asia Water Forum. Nusa Dua, Bali.	1 case Study	1	No	Research Paper
37	Majule, A. E. (2010). Towards sustainable management of natural resources in the Mara river basin in Northeast Tanzania. Journal of Ecology and the Natural Environment, 2(10), 213-224.	1 case Study	1	No	Journal Article
38	Manor, S & Hagali, Z. (2002). Case Study from Israel. Survey on Irrigation Modernization. The Hefer Valley Water Users Association. FAO	1 case Study	1	No	Report
39	McPartlon, Emily, "Testing Ostrom: an Analysis of Water User Commitees in Uganda" (2016). Master's Thesis. Paper 180.	1 case Study	1	Yes	Thesis
40	Mitchell, W. P. 1977. Irrigation Farming in the Andes: Evolutionary Implications. St. Martin's Press, New York, USA. 36-59., Mitchell, W. P. 1976. Irrigation and Community in the Central Peruvian Highlands. American Anthropologist. 78:25-44.	1 case Study	1	No	Journal Article
41	Morrow, C. E., & Hull, R. W. (1996). Donor-initiated common pool resource institutions: the case of the Yanesha forestry cooperative. World Development, 24(10), 1641-1657.	1 case Study	1	Yes	Journal Article
42	Nilsson, T. (2001). Management of communal grazing land: a case study on institutions for collective action in Endabeg village, Tanzania. Tekniska högskolan i Stockholm.	1 case Study	1	Yes	Thesis
43	Peters, P. E. (1994). Dividing the commons: politics, policy, and culture in Botswana. Charlottesville: University Press of Virginia.	1 case Study	1	No	Book
44	Pinkerton, E., & Weinstein, M. (1995). Fisheries that work: sustainability through community-based management. David Suzuki Foundation, Vancouver, BC.	Comparative Case Study	4	No	Report

45	Pomeroy, R. S., Katon, B. M., & Harkes, I. (2001). Conditions affecting the success of fisheries co-management: lessons from Asia. Marine policy, 25(3), 197-208.	Comparative Case Study	45	No	Journal Article
46	Quinn, C. H., Huby, M., Kiwasila, H., & Lovett, J. C. (2007). Design principles and common pool resource management: An institutional approach to evaluating community management in semi-arid Tanzania. Journal of environmental management, 84(1), 100-113.	Comparative Case Study. Statistical Analysis	38	Yes	Journal Article
47	Romana, P., & los Reyes, D. (1980). Managing Communal Gravity Systems: Formers' Approaches and Implications for Program Planning: Final Report Submitted to the National Irrigation Administration by the Institute of Philippine Culture in March 1980. Institute of Philippine Culture, Ateneo de Manila University.	1 case Study	1	No	Report
48	Ross, A., & Martinez-Santos, P. (2008) The challenge of collaborative groundwater governance: four case studies from Spain and Australia. DOI: http://www.newater.uni-osnabrueck.de/caiwa/data/papers%20session/F4/ARPMSCAIWA.pdf	Comparative Case Study	2	Yes	Research Paper
49	Rubinos, C. (2013). Institutional Analysis of Water Management for Agriculture in the Chancay-Lambayeque Basin, Peru. Master Thesis. Arizona State University.DOI: https://seslibrary.asu.edu/node/270	1 case Study	1	No	Thesis
50	Said, S. (2006). Irrigation in Africa: Water conflicts between large-scale and small-scale farmers in Tanzania, Kiru Valley. DOI: http://www.diva-portal.org/smash/get/diva2:16426/FULLTEXT01.pdf	1 case Study	1	No	Research Paper
51	Sarker, A., & Itoh, T. (2001). Design principles in long-enduring institutions of Japanese irrigation common-pool resources. Agricultural Water Management, 48(2), 89-102.	1 case Study	1	Yes	Journal Article
52	Schweik, C. M. (2000). Optimal foraging, institutions and forest change: A case from Nepal. Environmental Monitoring and Assessment, 62(3), 231-260.	1 case Study	1	No	Journal Article
53	Sekher, M. (2000). Local organisations and participatory CRP management: Some reflections. Banglore, India: Institute for Social and Economic Change DOI: http://www.isec.ac.in/Local_organisations_and_cpr_participatory.pdf	1 case Study	1	No	Research Paper
54	Steins, N. A and Edwards, V. M (1999). Collective Action in Common-Pool Resource Management: The Contribution of a Social Constructivist Perspective to Existing Theory. Society and Natural Resources 12(6): 539–557.	1 case Study	1	Yes	Journal Article
55	Stern, P. (2011). Design principles for global commons: Natural resources and emerging technologies. International Journal of the Commons, 5(2).	1 case Study: The Global Commons	1	Yes	Journal Article
56	Sundberg, J. (1998). NGO landscapes in the Maya biosphere reserve, Guatemala. Geographical review, 88(3), 388-412.	1 case Study	1	No	Journal Article
57	Tang, S. Y. (1992). Institutions and collective action: Self-governance in irrigation. ICS press.	Comparative Case Study	47	Yes	Book
58	Trawick, P. B. (2001). Successfully governing the commons: Principles of social organization in an Andean irrigation system. Human ecology, 29(1), 1-25.	1 case Study	1	Yes	Journal Article

59	Tucker, Catherine, J. C. Randolph, and Edwin J. Castellanos. 2007. Institutions, biophysical factors and history: An integrative analysis of private and common property forests in Guatemala and Honduras. Human Ecology 35(3):259–274.	Comparative Case Study	2	No	Journal Article
60	Vandersypen, K., Verbist, B., Keita, A. C., Raes, D., & Jamin, J. Y. (2009). Linking performance and collective action—the case of the Office du Niger Irrigation Scheme in Mali. Water resources management, 23(1), 153-168.	1 case Study	1	No	Research Paper
61	Vogt, N. D., Banana, A., Gombya-Ssembajjwe, W., & Bahati, J. (2005). Understanding thestability of West Mengo forest reserve boundaries. ACCEPTANCE PAGE, 47.	1 case Study	1	Yes	Journal Article
62	Wade, R. (1988). The management of irrigation systems: How to evoke trust and avoid prisoner's dilemma. World Development, 16(4), 489-500.	1 case Study	1	No	Journal Article
63	Wang, X., Otto, I. M., & Yu, L. (2013). How physical and social factors affect village-level irrigation: An institutional analysis of water governance in northern China. Agricultural water management, 119, 10-18.	Comparative Case Study	1	No	Journal Article
64	Young, O. R. (1999). Governance in world affairs. Cornell University Press	1 case Study	1	No	Book

We address the research question: What considerations should we bear in mind when using the design principles for theory building and/or policy making in order to obtain clarity and comprehensiveness? In this sense, the literature review was guided by the following specific questions for each design principle:

1) Which is Ostrom's explanation of the DP? We analyze component by component[2] each DP as explained in Ostrom (1990, 2005 and 2009).

2) Which are the desired outcomes and which are the potential threats that are intended to be prevented with this DP?

3) Which are some of the studies that have conflicting arguments among them for this DP?

4) Which circumstances have been found so far that would make the implementation of this DP more or less likely?

2 The Design principles are considered as general features for "successfully" managed SES. Subdividing the DP in components or subsets can be useful exercise for diagnostic approaches (Young, 2002; Ostrom, 2007)

5) Based on these studies, which special consideration—that was not specified or clarified before—should we have related to this DP?

Results, Analysis And Recommendations

Commons governance outcomes. One of the reasons why CPR governance theory building is a difficult endeavor is because of its difficulty agreeing on the normative component: the outcome of systems governance. Initially scholars were looking to avoid, as called by Hardin (1968), "*the tragedy of the commons*," which would strictly imply no over-exploitation of a resource, and thus avoidance of the collapse of a system centered on a CPR. When Ostrom proposed the DPs, she said that those were the regularities that she found in self-managed long-enduring systems. By long-enduring she meant "*resource systems, as well as the institutions, [that] have survived for long periods of time*" (Ostrom 1990, p. 58)[3].

Following the sequence of studies from the "tragedy of the commons" to Ostrom's research, it was logical to aim for systems that last over time. However, we agree with Berkes (2006) in that "long-enduring" as an outcome measure can be problematic in contemporary SES because of the novel perturbation of globalization (including climate change). It thus becomes necessary to include in the analysis the type of perturbations, if any, that the system has been exposed to, and analyze its level of

[3] Ostrom (1990) clarifies that long period of time means at least 100 years, and that institutions have not been necessarily fixed, but that they have been robust, as defined by Shepsle (1989). *"Shepsle (1989b, p. 143) regards "an institution as 'essentially' in equilibrium if changes transpired according to an ex ante plan (and hence part of the original institution) for institutional change." In these cases, the appropriators designed basic operational rules, created organizations to undertake the operational management of their CPRs, and modified their rules over time in light of past experience according to their own collective-choice and constitutional-choice rules. (Ostrom 1990, p. 58)*

robustness to them. Thus, the need to make a distinction between system longevity, because of solving the inherent social dilemmas of CPRs, and the system robustness is evident (Steins and Edwards 1999). Another interesting and relevant question from this analysis is what is the interplay between overcoming social-dilemmas and system robustness to potential shocks? In the Piura basin described in chapter 4, for example, the farmers' collective action for improving public provisioning (disaster prevention) was triggered by a series of environmental events.

We use the term robustness in regard to SES as the adaptability to disturbances, such that some desired system characteristics are maintained even though the behavior of the SES components have fluctuated (Carlson and Doyle 2002, Anderies, Janssen, and Ostrom 2004; Janssen and Anderies 2007). This fluctuation is normally due to a perturbation, and because different perturbations have different impacts on the system adaptability, the analysis of robustness needs to address a particular perturbation (Anderies et al. 2004). Moreover, when a system is robust to one perturbation, it becomes fragile to a different perturbation (Anderies and Janssen 2011). This means, that there exist robustness–fragility tradeoffs inherent in different designs. Under these circumstances defining a CPR management as successful because of its longevity without analyzing potential perturbations to its components may be problematic.

Another reason why the longevity of SES can be a problematic measure is because it may be that a system that has lasted for centuries has not necessarily been managed properly. For example, there are many irrigation systems that last for long periods of time with disruptive conflicts, impoverished farmers, and / or polluted water. Take the case of the irrigation system in the Usangu basin, in Tanzania. The system dates back to the early 19th century, but disparities, poverty and land degradation are current problems (Cleaver & Franks, 2005)

Ostrom was well aware of the need to take into account other outcome indicators, such as the need to achieve “productive outcomes” (Ostrom 1990, p 5), or “appropriation rule compliance” (Ostrom et al. 1989, p 10), or the outcome variables that she proposed in the SES framework (Ostrom, 2007): efficiency, equity, accountability, sustainability, resilience, bio-diversity, and indicators of externalities to other SESs. However, there is still the challenge of differentiating clearly between “different measures and dimensions of commons outcomes” in the analysis, and to avoid vague terms such as “sustainability”, “long-term viability” or “conditions of the commons” as proposed by Agrawal (2014, p 89).

A more helpful exercise for theory building (although contested[4]) is to use more precise definitions of success rather than using vague definitions that limit comparability of results. Baggio et al. (2016), for example, proposed as a measure of outcome: “Those that have not displayed ecological deterioration, nor conflict or trust issues” (Baggio et al. 2016). As in this last case, it is sometimes useful to include more than one measure of success. For example, in the Agcuyo irrigation system (Romana & los Reyes, 1980) the public infrastructure (dam) is always destroyed after strong rains. This causes economic damages because the community grows fewer crops as a consequence, and users have to repair the dam after the rain. In this case there is appropriation and provisioning rule compliance, and there are no social conflicts, but the farmers are still impoverished. If we

[4] Some researchers argue that the definition of success should come from the community itself, though this definition could be biased or may neglect its impact on another system.

consider only the first two outcomes (rule compliance and disruptive conflicts), then it may seem that this case is successful, however, if the aim of the system actors is to achieve productive outcomes, then the system is not successful.

Another option for classifying SES outcomes is to assess a more continuous indicator rather than dichotomizing governance performance. For example, in the Agcuyo case, since it has 2 out of 3 measures (if those 3 measures are chosen for the analysis) of desired outcomes, then its performance can be seen as moderate, whereas a case that has 3 out of 3 desired measures can be seen as strongly successful.

Findings about each design principle

DP 1: Clearly defined boundaries. "The boundaries of a resource system (e.g., irrigation system or fishery), and the individuals or households rights to harvest resource units are clearly defined" (Ostrom 2005, p 259*)*. Boundary rules should state who can access or enter the resource system, who can appropriate or harvest the resource unit, who can manage and, who can exclude others from all these types of rights of the resource system (Ostrom, 2008)[5].

We identify three components of this DP: (1) clearly defined physical boundaries, (2) clearly defined user group (access and/or appropriate a resource), (3) clearly defined managers, and (4) clearly defined individuals who can exclude others—not included in 2 and 3—from the benefits created in the system. The benefit of having clearly defined

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5 Schlager and Ostrom (1992) identify five property rights for the use of CPR: access, withdrawal (harvest), management, exclusion and alienation. Alienation is generally related to the ownership of private property, and it is not mentioned in DP1 since the study was performed on community managed CPRs. This DP suggests that there should be position rules for each type of property right (except alienation).

physical boundaries is that everyone can know what is being managed and where they may go or not go (Ostrom 1990). The advantages of clearly defining the members of the resource system is that they know the size of the population among whom they will share the resource units and know who has access rights. The advantage of knowing the managers is that they know the decision making process with regard to the system. Finally, the advantage of the fourth component is that if users collectively arrived at some agreement to produce some benefits—which is the purpose of collective action—the risk of these benefits being reaped by others who have not contributed to the collective action (free-riding behavior) is reduced. If non-members find the resource valuable, they may want to use it, and potentially overharvest it (Ostrom 1990), or damage the ecosystem. Despite the relevance of all the components of this DP, we found in our literature review that less attention is paid to components 3 and 4 of this DP. Cox et al. (2010), for example, divided the DP1 into two parts: DP1A "Community Boundaries" and DP2B "Resource Boundary." This shows the importance of discussing the components inside each DP to make sure we capture their full conceptualization in the analysis.

One aspect of this DP that has been a matter of discussion is the flexibility of the definition of boundary rules. Some authors have interpreted this DP as proposing to define fixed boundaries and have criticized it for been too rigid. Cousins (2000) found that in semi-arid regions of Africa the resource availability (e.g. water, grassland) varies spatially and temporally, and users require access to the resource from different areas at different times. Similarly, Quinn et al (2007) argues that to increase rangeland carrying capacity when an area is about to be over-grazed, users need to move to other regions and thus, they proposed fluid rules to avoid impoverishing users and over-grazing in some parts of the range. However, it is still not clear how fuzzy rules and flexible boundaries affect the outcome of resource management. Take the case of the Mali irrigation system (Vandersypen et al. 2009) where the boundary rules were so flexible that they had to discuss how to apply it in particular cases every time water was scarce. On the other hand, very rigid rules are also problematic. In the Mara River Basin, where clan migration is a problem, boundary rules are defined by clans in such a way that they are forbidden to migrate to other territories. This generates high population density in some of the clans' territories (Majule, 2010). Wade (1988) suggests that rules can be flexible but they still need to be specific, and managers or decision makers for this matter should be aware that there is a trade-off between being specific and flexible.

We think that this trade-off between clarity and flexibility can be reduced if boundary rules are combined with appropriation and provision rules. The necessity of these two rules is not explicitly mentioned in the DPs, though it is implicitly mentioned for the discussion of some of their characteristics in DP 2. We think that appropriation rules very much need to be combined with boundary rules because it does not help to avoid open access scenarios if defined users are allowed to appropriate as much as they desire. Moreover many times boundary rules are subject to compliance with appropriation and provisioning rules. Some systems define their social boundaries subject to compliance with other rules such as land tenure, water and management tariff payment or other provisioning rules, user registration, resource units appropriation rules, among others. In the Chancay–Lambayeque irrigation system for example, social boundaries are linked to land tenure within the physical boundaries, but they are not allowed to withdraw water if they do not pay a water tariff first. We propose then, to include a fifth and a sixth component to this DP: (5) clearly defined appropriation rules and (6) clearly defined provisioning rules. Steins and Edwards (1999), Berry (1993, 1994) and Peters (1994) studied cases where users of the same resource system, used different resource units or used the same resource unit but for a different purpose (e.g. forest, water for irrigation and other uses), and they found that resource and user's boundaries are "extremely high cost to define." We argue that this can be solved with the help of appropriation and provision rules. In the Piura Basin for example, there are temporary water users who can appropriate water only when water is abundant (appropriation rule) and subject to the payment of water tariffs (provisioning rule) (see chapter 4).

Table 2.3

DP1 With Proposed Modification

DP1: Clear Distribution Rules
Components:
1. Clearly defined physical boundaries
2. Clearly defined user boundary rules
3. Clearly defined manager
4. Clearly defined who can exclude others from the system
5. Clearly defined appropriation rules
6. Clearly defined provisioning rules

Interrelationship with other design principles. As we can infer from the discussion above, the characteristics of the boundary rules should depend on the situated conditions (we will discuss this further on DP 2), and since SES are constantly changing, rules that govern them should change accordingly. The mechanism of rule changing is described in DP 6 (Conflict resolution mechanisms) and who should be involved is described in DP 3 (Collective Choice). Also, rules that are part of this DP should also be enforced as suggested by Morrow and Hull (1996), but since we believe that every rule of the system should be enforced, we suggest including it in DP 4 (Monitoring).

Context matters. As we know from Ostrom (1990), context matters. We have done here an initial exercise that might be useful to map out a direction for future research with regards to how context matters for this DP. We identify 3 crucial aspects to take into account for boundary rules crafting:

A) Social (including political) and biophysical congruence. We found in some cases that the physical boundary is different than the political boundaries, making both boundaries fuzzy (Quinn et al. 2007, Cousins 2000) and problematic to govern. One potential way to overcome this problem is by relying on other mechanisms such as the use of physical infrastructure to delimit resource systems. Vogt et al. (2005) found that in many forests of Uganda with fuzzy boundary rules, deforestation was a big problem; however, in one forest that had been closely demarked with cairns that depicted drawings of tree species that could be (could not be) harvested, forest conservation was quite effective. It might be that for these cases, the presence of other principles becomes even more relevant; for example, an adequate coordination with managers of the related communities that share the ecological region (DP 8, nested enterprises).

B) Information flow. One type of information challenge concerns the knowledge of SES itself. Groundwater systems, for example, have diffuse hydrological boundaries and are difficult to define due to the connection of individual aquifers with other aquifers and surface water (Gonzalez-Aubone et al, 2014). It is likely that this information problem will be solved with progress in science and technology, but not all the systems will necessarily have access to this type of information immediately. In the Dubre system of Haiti (Boyer & Van, 2011), for example, users did define the ecological boundary of their irrigation system. However, the author considers that it was *not* clearly defined since the levels of the river flow were unknown, and thus, this created problems of water allocation for individual users. Today's technology allows for the measure of river flows, but in that particular system, users did not have the financial capacity to acquire such technology. Also, as Schlager, Blomquist, and Tang (1994) stated, there are some resources that are generally easier to measure and control than others, which depends heavily on the mobility of the resource and its storage.

Another type of information challenge occurs when governmental authorities define the boundaries of a SES, such as paper parks, and then fail to make sure that participants are aware of it (Hayes 2004, Dietz, Ostrom, and Stern 2003). In paper parks that have failed in their management, it is generally because users are not aware of the paper parks, and thus are not able to enforce them locally. Sundberg (1998), for example, found that the boundaries of the Maya Biosphere Reserve in Guatamala City are well defined on maps, but 80% of surveyed farmers were unaware of the Reserve boundaries.

C) System size, networks (sub-groups) and population growth. Literature of the commons suggests that larger groups and more heterogeneous groups are more likely to fail in collective action. However, there are some cases in which SESs with these two characteristics managed to overcome that problem by dividing the management in sub-organizations in a polycentric governance structure (Keohane & Ostrom 1994, Ostrom 2012). How to define these sub-groups and their boundaries may be relevant and thus applicable to this principle. Thus, even though we found authors like Stern (2011), who suggests that for the global commons DP 1 is less significant because there is only one-way to set boundaries for the world, DP 1 may be relevant for defining sub-groups.

DP2: Proportional equivalence between benefits and costs "Rules specifying the amount of resource products that a user is allocated are related to local conditions and to rules requiring labor, materials, and/or money inputs." (Ostrom 2005, p. 259).

We identify four components of this DP: (1) There should be appropriation rules indicating how much, when, and how different products can be harvested, (2) and provision rules to determine how members will bear individually the costs of the operating shared system, (3) Provision rules should be proportional to the individual benefits (benefits that are derived from appropriation), so that they perceive that rules are fair. "If some people pay low costs but get high benefits over time, this inequity frustrates the other participants and may cause more and more to consider the rules unfair and refuse to abide by them." (Ostrom, 2009, p 40). And, finally, (4) appropriation rules need to be related to local conditions. The cases that Ostrom studied were relatively small SES, and local conditions was the proper term, however, if we intend to expand the DP for large-scale SES also, we need a different term. We think that the term "situated conditions" is a better fit.

The first two components "appropriation and provision rules" were discussed in the previous DP, and we think that because of their strong interconnection with boundary rules they should be included in the first DP that we have renamed as "clear distribution rules." Moreover, we think that components (3) Cost benefit equivalence and (4) The importance of considering situated conditions, should be applicable to all the rules, and thus, to all the DP when possible. We discuss further how (3) and (4) are related to other principles throughout the paper, however a quick example is the case of DPs that suggests monitoring of users behaviors. With respect to (3), if the perceived benefits of monitors are lower than their costs, they may end up relaxing their work, or accepting bribes to compensate for their costs of monitoring. With respect to (4), the perceived benefits of the monitor may not be necessarily monetary, but in the shape of sense of social contribution or prospective in the governance system. Then, how to design the rules to incentivize monitors to be aligned with the systems' desired outcome depends on the shape of the monitor's values.

We have already discussed how context matters for DP 1. We show for the other DPs the importance of situated conditions as well. It is important to highlight that the term "situated conditions," does not refer only to ecological conditions, but also includes social conditions. This idea has been accepted by Ostrom and is clearly expressed in the Institutional Analysis and Development Framework (Ostrom, 2011) as well as in the Social-Ecological Systems Framework (Ostrom, 2007), where authors manifest the importance of specific variables of the biophysical and social aspects of the system that, combined with the institutional arrangements, affects a determined outcome. We claim here that there should be an explicit statement in this DP that all of the components of the DPs should have these situated conditions in mind when being designed.

Last, this DP has a special characteristic that makes it different from the other DPs. When an exercise for identifying if rules fit with the situated conditions, it is extremely difficult to determine how well its fit is with all situations and conditions and without including the analysis of the outcome of the system, and thus, it cannot be really assessed as a causal condition for an outcome. We believe that this very important aspect of rules should be of special attention for practical and methodological reasons. It is a DP that has to be taken into account across all the other DPs. If we consider this requirement as such, we could move on to identify, as mentioned in the preceding paragraph, how specific conditions (that are included in this DP) and other DPs interact with each other to produce different outcome.

Table 2.4

DP2 With Proposed Modification

DP2: Rules Congruence
Components:
1. Congruence between rules and physical characteristics of the system
2. Congruence between rules and social characteristics of the system
3. Cost and benefits congruence among, and between rules.

DP3: Collective Choice Arrangements. "Most of the individuals affected by a resource regime are authorized to participate in making and modifying the rules" Ostrom (2009). This DP addresses the need to design rules that fit with local circumstances, including participants' perception of fair rules. Empirical research has shown that fairness is a crucial attribute of the rules needed to avoid free-riding behavior (Wade, 1988), and many scholars (Chakraborty 2004, Trawick 2001, Tang 1992 and Lam 1998, Marwell and Ames 1981, Margolis 1982) have supported the importance of fairness for sustainable management of CPRs.

Ostrom (1990) argues that the resource users who are in more direct contact with the resource and exposed to the system dynamics on a daily basis know better than others about the specifics of the interaction and conditions in a SES. She argues that they should participate in the rule making process on a constant basis to include modifications needed when changes happens to the specific characteristics of their settings. However, there are many cases in which users are in charge of rule crafting and have failed, and other situations where users not in charge of rule crafting have succeeded. An example of the former are the cases studied by Nilsson (2001) and Bardhan (2000), who found that elites prevented others from participating in rule-making processes in Tanzania and India, respectively. Cleaver and Franks (2005) argue that, in the cases that they studied, because of their high opportunity cost, users with few resources tend to be excluded or even exclude themselves from participating because of high opportunity cost. In all these cases, even though most of the users had the right to participate in rule crafting, this was not a de facto rule since only wealthy users affect rules. Sekher (2000) found that in India the wider the representation of the community in the organization, the better are its chances of securing local cooperation and rule confirmation for managing and preserving the resource. Then, it seems that it helps if most of the users participate in decision making, however, it is not enough to just have the right to do it, it is important to consider situated conditions (such as income level, distance to travel to participate, local elites, etc.) to guarantee its viability, and to ensure that the perceived benefits of participating outweighs the cost of doing so (DP 2)

Furthermore, if the rationale of this DP is that decision makers should have the best available information to fit rules with the situated context, then there might be alternative ways to achieve that outcome. On one hand, it is not always true that a system's users have complete information, especially not of novel shocks, social trends, ecological changes; and on the other hand, we may want to consider possible externalities from or to another interconnected system or sub-system (Ostrom, 2007). Then depending on the situated condition, other non-users actors should be involved in the rule crafting process for achieving a desired outcome. For example Fleischman et al. (2014) described how systems were able to successfully overcome the CPRs challenges by replacing the original requirements of this DP by other similar-in-purpose mechanisms that are also linked with the DP6. In the Indonesian Forest, for example, this DP was absent, but an improved democratic system guarantee users' participation.

In any case, the focus of this DP is on making sure that managers have the right information based on who needs to participate to provide the information, which depends on the situated conditions. Where and how they may interact to make the information flow is a concern of DP 6 "Conflict resolution mechanism" that we analyze below. It is important for the fulfillment of this DP, as we are proposing it, to have clear working rules about who should participate and the decisions that will be made (e.g., voting rules). We would only say that this DP is fulfilled when most of the users' (as well as other relevant non-user stakeholders') points of view and knowledge are effectively taken into account[6].

[6]It is easy to confuse this DP with DP6, because how effectively stakeholders opinion and knowledge are taken into account will also depend on how they are actually discussing conflicting topics. In some systems where the government intervenes in important decisions, they invite users to participate; however, the communication in the meetings flows only in one direction, and users' perspective are not necessary taken into account. In some other cases, the meetings that are organized are far from users houses or are held in critical working hours.

Table 2.5

DP3 With Proposed Modification

DP3: Stakeholder Effective Participation
Components
1. Users point of view and knowledge are effectively taken into account
2. Other relevant non-users' point of view and knowledge are effectively taken into account.

DP4: Monitoring. "Monitors, who actively audit biophysical conditions and user behavior, are at least partially accountable to the users and/or are the users themselves" (Ostrom 2005, pp 259).

We identify three components in this DP. One is that there are monitors, or there is a monitoring mechanism of how users comply appropriation rules (e.g. harvesting). This is important because the next challenge after convening the rules is to actually follow them, and in CPRs systems actors generally face the temptation of non-compliance, given that, if others do comply, defectors may increase their individual benefit. This is why such situations are referred to as social dilemmas, because actors face the dilemma of collaborating with the group by following the rules, or just looking after their self-interest and betraying the agreement (Ostrom, 1990).

Many authors agree that appropriation rule enforcement is crucial for collective action (Gibson, Williams, and Ostrom, 2005; Ostrom and Nagendra, 2006; Hayes and Ostrom, 2005; and Schweik, 2000). We agree that this component is important, but we suggest a modification. Morrow and Hull (1996, 1643), for example, suggested rephrasing the first design principle to guarantee enforcement of boundary rules. Many authors (Gibson, Williams, and Ostrom 2005; Hayes and Ostrom 2005, Ostrom 2009) have supported this suggestion. However, as with the example of boundary rules we could analyze other rules that may affect users' and managers' behaviors, such as the compliance with provision rules. We can argue that the congruence between appropriation and provisioning rules are necessary, but for it to be really fair, both need to be enforced. Many of the studies of complex novel CPRs pay no attention to monitoring provision rules, for example, so we find it relevant to explicitly mention the importance of rules enforcement in general, including appropriation rules, boundary rules, provision rules, but other rules also.

The second component of this DP is that monitors need to be accountable. Sometimes monitors are disconnected with the final goal of monitoring by virtue of being appointed by higher levels of governance; and, if they are not held accountable, they can let users appropriate more than their allotment for retribution, or be somehow careless with rule compliance. When users need to monitor the monitors, collective action becomes very costly. Brewer et al. (1997) propose to instead consider monitors' incentives too so that the benefit of doing their job is higher than the cost of not doing it. One incentive is to reward with a career path in the system subject of their monitoring. In that sense payoff congruence (a component of DP 2) should also be applicable for monitors, and using the same logic, we can suggest this proposition for managers in general. Moreover, how actors decide to monitor the system should also depend on the local context. If it is small and terraced as in the cases of Arequipa (Tarwick, 2001), then there is less need to hire special monitors; actors can naturally monitor others' behavior. If the system is productive enough to allow users to invest in a high technology computerized monitoring mechanism as in the case of Campo de Dalías (Lopez-Galvez & Villasante, 2001), their monitoring mechanism then can be even more precise.

The last component of this DP is the environmental monitoring. Managers need to know the ecological condition of the system to make decisions according to the difference between the desired outcome and the observed one (Ostrom, 2008). We found, that researchers have focused less on this component of the DP. For some type of CPR governance, such as wildlife, this is a key component given that international treaties specially focus on the resource condition. We also find it relevant to add as a component a human-made hard infrastructure monitoring mechanism, such as reservoirs and canals, for irrigation systems, or fishing technologies, so managers can make decisions accordingly for its maintenance or regulation, respectively, that ultimately will affect the outcome of the CPR management. The functioning of this type infrastructure can affect users' payoffs and change incentives for cooperating resulting in changes in users strategies.

Ostrom (2005) suggests that it is preferable that users are the monitors because they get to know when others are complying with the rules, which increase users' trust in the agreement and a stable sense of fairness. However, this may not be necessary if monitoring with a transparent monitoring system. This is especially relevant for large-scale systems, in which it is not possible for users to monitor themselves. We suggest a fifth component: it is also important that users are aware of rules compliance.

One purpose of monitoring actors' behavior is to send a sign to actors that if they do not comply with rules there is some possibility of getting caught, which, depending on the sanction for non-compliance, may reduce the payoff (benefit) of non-compliance (monetary and non-monetary, sometimes users payoffs also incorporates a cost of embarrassment), reducing the temptation to defect. Then, even if monitoring is functioning well, when a defector is caught and there is no sanction – or nothing happens (even if it is just warning, admonition, or the embarrassment of getting caught) then the act of monitoring is not necessarily translated into enforcement. Users need to know not only that if they defect they might be caught, but also that if it happens, then his or her – monetary or non-monetary- payoffs may be reduced. Take as example the Chancay-Lambayeque irrigation system case, where infractors appropriated water outside of the rules in front of the monitors. This DP and DP5 (Sanctioning) are strongly associated (Gibson, Williams & Ostrom, 2005).

Table 2.6

DP4 With Proposed Modification

DP 4: Monitoring
Components
1. Presence of a monitoring mechanism of rule compliance (Relevant rules to be defined depending on the context of the system, but some examples are) a. Boundary rules b. Appropriation rules (either as choice or scope rules) c. Provisioning rules d. Other choice rules not included in appropriation or provisioning rules e. Information Rules f. Position Rules g. Aggregation Rules h. Payoff rules 2. Monitoring mechanisms are accountable 3. Users know the level of rule compliance 4. Monitoring of the ecological condition 5. Monitoring of the human-made hard infrastructure

DP5: Graduated Sanctions. "Users who violate rules in use are likely to receive graduated sanctions (depending on the seriousness and context of the offense) from other users, from officials accountable to these users, or from both." Ostrom (2005)

This DP addresses the need for a negative consequence for users that do not comply with rules by receiving a type of sanction. This is the first component of this DP. A second component is that the determined sanction should be graduated in the sense that it depends on the type of infraction, the degree and the frequency. When sanctions are graduated, the system is tolerant to mistakes, but at the same time communicates to the offender that the manager and/or other users have notice his non-cooperative behavior (Ostrom, 2009).

It is key here to suggest an explicit mention of sanctions enforcement, which we think are as important as the other components but is not mentioned in the original descriptions of the DPs. In many systems, graduated sanctions are clear but are, however, never applied. See for example how in the Chancay-Lambayeque Basin in Peru, offenders never pay the fees related to their sanctions (Rubinos, 2013). If users think that it is very likely that sanctions will be imposed if they do not comply, then it reduces their incentives to defect. On the other hand, it increases their confidence that others will comply with the rules. Then, it is also important to communicate to others when a sanction has been imposed to increase actors' trust in rule enforcement. As we can see, monitoring and sanctioning are strictly connected since there is no sense of monitoring if there would not be any consequence of being caught, and it is not possible to be caught if there is not a type of monitoring in the system. We suggest then, that DP4 (monitoring) and DP5 (graduated sanctions) should be combined in only one design principle given their strong interdependence.

Sanctions can be in any form, which will depend on the situated conditions. There are cases where reputation is more valued than money, thus monetary sanctions would not be as effective as the threat of others knowing about their non-cooperation, as in the case of the Nishikambara irrigation system (Sarker & Itoh, 2001). Moreover, as in the case of monitoring, we believe that sanctions are necessary not only for non-compliance of appropriation rules, but also for infraction in other rules, and they can be also applied to actors that hold different positions in a system (users, monitors, managers, etc.)

Table 2.7

DP5 With Proposed Modification

DP 5: Sanctions
Components
1. There is a negative consequence for users that do not comply with rules by receiving a type of sanction.
2. Graduated sanctions depending on type of infraction, the degree and the frequency.
3. Sanctions are effectively enforced
4. Users know when sanctions are imposed

DP6: Conflict Resolution Mechanism. "There are rapid, low-cost, local arenas in which to resolve conflict among users or between users and officials" (Ostrom 2005, 259).

Conflicts (discrepancies) are necessary for social construction, but if the structure of a system is too rigid, then conflicts scale into social problems (Stamm & Aliste, 2014). This DP represents the sole governance component that addresses the capacity of the system to solve conflicts. Human beings in general have different interpretation of rules and situations as well as interests (Ostrom, 2008), thus it becomes critical to discuss those potentially conflicting perspectives. It is then necessary to include in the system mechanisms to communicate conflicting positions, to be able to come up with solutions, and, if necessary, change the institutions. Generally, authors use the idea of conflict with a negative connotation. Huntjens et al. (2012) for example, differentiate mechanisms for conflict prevention and resolution, which manifest the existences of conflict levels. Conflict resolutions mechanism and spaces can be present at different scales, depending on the number of users involved and the type of conflict. One way of resolving conflicts (different perspectives) at the individual level is by different type of communication. This may be one of the reasons why communication among users has been found to be important for collective action in lab experiments (Ostrom, 2010).

When it is not possible to solve conflicts through communication of the conflicting parties, then neutral formal or informal arbiters of law (e.g. judge, mediator, tribunal of elders, a respected leader, a priest, etc.) may be necessary as proposed by Ostrom (1990, 2005). The characteristics of these conflict mechanisms will depend then in the situated conditions. For example, Ostrom's explanation of this DP mentions that the mechanism should be "rapid," however, we argue that this should depend on the situated conditions. Gautam and Shivakoti (2005) argue that systems that are more exposed to novel shocks will need to coordinate and share information for fast decision making. However there are some systems that may prefer to avoid rapid local arenas to resolve conflicts, and take their time to process the nature of the conflict, as in the case of the Usangu system in Tanzania (Majule, 2010).

As we mentioned when analyzing DP3, which actors should participate in rule crafting is not a matter of this DP; DP6 includes the interaction where different opinions and situations are exposed and considered to solve conflicts, which may imply or not, rules modification.

Table 2.8

DP6 With Proposed Modification

DP 6: Conflict Resolution Mechanisms
Components
1. Different opinions and situations are exposed and considered in order to solve conflicts, which may imply or not, rules modification.
2. This should be considered for different levels of conflicts. Conflict of perspective are considerated in this DP, then simple communication is also part of this component

DP7: Minimal Recognition of Rights to Organize. "The rights of users to devise their own institutions are not challenged by external governmental authorities, and users have long-term tenure rights to the resource" (Ostrom 2005, pp 259)

The components that we can identify in this DP are: (1) that users have the right to devise their own institutions (which is Ostrom's original proposition of DP 3)[7], (2) that this right is not to be challenged by external governmental authorities (which is, as we will explain better, contained in DP 8), (3) that users have long-term tenure rights (which is DP 1, as we already explained), and (4) that users have the right to organize.

Because this DP suggests that users should have recognized authority to design the institutions in a system, this DP, as it is, is applicable only for self-governed systems

[7] Some authors, like Fleishchman, Ban, Evans, Epstein, Garcia-Lopez and Villamayor-Tomas (2014) confess that for large scales systems it is hard to differentiate DP 7 from DP 3.

as those that Ostrom studied. As we explained in DP3, many systems are interconnected with other systems of different scales either by the resource system (e.g. river, groundwater in the water cycle, energy consumption, air pollution and forestry activity are strongly connected) or by the outcomes of governance (e.g. economic dependence, multi-systems externalities). If we want to target systems that are nested or interconnected to other system, users may not have the authority to *fully design* their institutions, because they have to consider how these rules affect or are affected by other actors in other systems. It is however important that they *at least participate in their design* (which is, as discussed before, DP 3). Moreover, regardless of users' degree of participation in rule making, it is also important that users have the right to organize. If users of a system are to coordinate rules and enforcement with actors from other systems, they need to coordinate among themselves first, and then bring a unified or discussed position. Even for large-scale and heterogeneous groups in a system, organizations at a micro level are critical for discussion among users. In the Acequias irrigation system in Texas, for example, the problematic characteristic of having a large and heterogeneous group of users was offset by the capacity of conforming modular networks that decomposed the large groups into subgroups, reducing the transaction costs of collective action (Cox, 2010). For even a larger scale as the global commons, the importance of networks or organizations in sub-groups may be critical for achieving collective action (Ostrom, 2012). However, how these sub-groups should interact among them and between other groups is a matter of discussion of the following DP.

Table 2.9

DP7 With Proposed Modification

DP 7: Rights to Organize
Components
1. Users have the rights to organize
2. Users effectively are part of a formal or informal organization that is not undermined by other instance of governance.

DP8: Nested Enterprises. "Appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities are organized in multiple layers of nested enterprises" (Ostrom 2005, p 259)

Ostrom's (1990) explanation of this DP was specific to vertical linkages. However in later publications (e.g. Ostrom 2005, 2009), she incorporated in the description of this DP the notion of polycentric systems as defined by Vincent Ostrom (1999, p 57): "one where many elements are capable of making mutual adjustments for ordering their relationships with one another within a general system of rules where each element acts with independence of other elements"

The only confusion that we found in the literature, is related to the term "nested," which implies levels of governances that are inside each other, and that omits the horizontal linkages that are very much needed for polycentric governance. A rewording of this DP may be necessary. We propose to change it to: "Effective relations with other tiers of rule-making authority (polycentric governance)." Where "effective relations" can mean that these authorities coordinate among each other so that their rules and their enforcement, as well as other governance activities, are adjusted for ordering their relationships.

This definition covers concepts that are proposed by other authors such as "multi-level governance," "multilayered institutions" or "multi-dimensional linkages" (Marshall, 2008; Poteete, 2012), "federated systems" (Agrawal, 2002), "cross scale interactions" (Berkes, 2002), and "agency coordination" (Wade 1988) that are suggested as important for the outcome of systems governance.

Table 2.10

DP8 With Proposed Modification

DP8: Appropriate relations with other tiers of rule-making authority (polycentric governance)
Components
1. Authorities coordinate among each other so that their rules and their enforcement, as well as other governance activities, are adjusted for ordering their relationships.

Concluding Thoughts

When Ostrom (1990) analyzed self-governing systems and found regularities in long-enduring systems, which she called designed principles, she identified core characteristics that enable collective action. To move forward in theory building we need to learn how these self-organizing components are influenced by contextual factors and vice versa. Some reviews have proposed some modifications of the DPs to make them clearer and enhance the study of them in real world cases. The need for this modification was even recognized by Ostrom (2009). We have incorporated those propositions as well as others from more recent literature and our own from both the analysis of these two and our own revision of cases.

We found that the desired outcome of system governance needs to be more specifically defined for CPR theory building. We show in table 2.11 outcome examples that have been proposed in the literature that we reviewed. We suggest that sometimes it might be helpful to choose more than one outcome for the analysis, as done by Baggio et al. (2016). A clear distinction needs to be made between a desired outcome that includes frequent perturbations (also called internal or external shocks), or less frequent perturbations. In the case of including less frequent and strong perturbations, we suggest a clear definition of the outcome (e.g. robust, resilient) to a particular shock (e.g. robust to droughts).

Table 2.11

Summary of Recommendations

<table>
<tr>
<td rowspan="14"><u>DP 2: Congruence</u>

<u>Contextual Variables</u>

System Size
Homogeneity/
Heterogeneity of
Groups
Leadership
Resource Dependence
Mobility
Storage Capacity
Market Integration
Market Proximity
External Government
Policies
Cross-Scale Linkages
Topography
Weather Predictability
Etc.</td>
<td><u>DP1: Clear Distribution Rules</u></td>
<td rowspan="14"><u>Outcomes</u>

Ecological Deterioration
Critical Conflicts
Trust Issues
Poverty Persistence
Appropriation Rules
Compliance
Provisioning Rules
Compliance
Efficiency
Equity
Accountability
Resilience to a
disturbance
Robustness to a
disturbance
Non externalities to other
CIS</td>
</tr>
<tr><td>1. Clearly defined physical boundaries
2. Clearly defined user boundary rules
3. Clearly defined manager
4. Clearly defined who can exclude others from the system
5. Clearly defined appropriation rules
6. Clearly defined provisioning rules</td></tr>
<tr><td><u>DP3: Stakeholder Effective Participation</u></td></tr>
<tr><td>1. Users point of view are effectively taken into account
2. Other relevant non-users' point of view are effectively taken into account.</td></tr>
<tr><td><u>DP 4: Monitoring</u></td></tr>
<tr><td>1. Presence of a monitoring mechanism of rule compliance
2. Monitoring mechanisms are accountable
3. Users know the level of rule compliance
4. Monitoring of the ecological condition
5. Monitoring of the human-made hard infrastructure</td></tr>
<tr><td><u>DP 5: Sanctions</u></td></tr>
<tr><td>1. There is a negative consequence for users that do not comply with rules by receiving a type of sanction.
2. Graduated sanctions depending on type of infraction, the degree and the frequency.
3. Sanctions are effectively enforced
4. Users know when sanctions are imposed</td></tr>
<tr><td><u>DP 6: Conflict Resolution Mechanisms</u></td></tr>
<tr><td>1. Different opinions and situations are exposed and considerate in order to solve conflicts, which may imply or not, rules modification.
2. This should be considered for different levels of conflicts. Conflict of perspective are considerate in this DP, then simple communication is also part of this component</td></tr>
<tr><td><u>DP 7: Rights to Organize</u></td></tr>
<tr><td>1. Users have the rights to organize
2. Users effectively are part of a formal or informal organization that is not undermine by other instance of governance.</td></tr>
<tr><td><u>DP8: Appropriate relations with other tiers of rule-making authority
(polycentric governance)</u></td></tr>
<tr><td>1. Authorities coordinate among each other so that their rules and their enforcement, as well as other governance activities, are adjusted for ordering their relationships.</td></tr>
</table>

For the analysis of each DP we made explicit the components that we identified that conforms each DP and analyzed it in detail. This exercise revealed specific overlaps and interrelationship among the DPs, which stress not only the need for their clarification, but also suggest a direction of change. We summarize in table 2.11 the proposed modifications. DP 2 indicates that rules should fit with the SES context and, as we discussed before, also across all the other DPs. This is important because this also implies that the DPs do not show their underlying causal processes alone (Ostrom 2009). “Situated conditions” comprehends a long list of variables that are grouped as “Biophysical Context” and “Attributes of the Community” in the Institutional Analysis and Development Framework, and “Social, Economic, and Political Settings,” “Resource Systems,” “Resource Units,” “Governance Systems” and “Actors” in the Socio-Ecological Framework. Many scholars have also suggested the inclusion of those variables such as system size, homogeneity/ heterogeneity of groups, leadership (Baland and Platteau 1996); dependence on a resource (Gibson 2001, Pinkerton and Weinstein 1995); market integration (Tucker 1999; Tucker, Randolph, and Castellanos 2007); urban or market proximity (Bardhan 2000, Cinner and McClanahan 2006); external government policies (Rodriguez 2007); cross-scale linkages (Berkes 2002; Young 2002); topography, weather predictability (Wade 1988), heterogeinity in information (Libecap, 1994) among others.

Generally, the study of these causal variables related to CPR conditions has been performed without incorporating the analysis of institutions and their characteristics. By making DP 2 transversal to all the DPs we can enable the understanding of how configuration of social, physical contexts and rules perform in different SES. The design principles components can become a checklist of variables to reference (similar to a framework, but organized for theory building), that can enable the construction of nested typologies of biophysical, social and governance arrangements that with empirical evidence prove to be relevant for increasing the likelihood of achieving a determined clearly defined outcome, as proposed by Ostrom (2007).

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CHAPTER 3

ROADMAP FOR POLICY MAKING: DESIGN PRINCIPLES ACCORDING TO IRRIGATION SYSTEM TYPE

Introduction

In 2009, Elinor Ostrom received the Nobel Prize for her contribution to our understanding of commons governance. She challenged the conventional wisdom and demonstrated with empirical evidence how commons users can successfully manage common-pool resources without privatization or regulation by central authorities. Ostrom (1990) used a meta-analysis (analysis of analyses) of 14 cases to discover that eight institutional characteristics were common to successful cases; she called these characteristics "design principles." The design principles are:

- clearly defined boundaries
- congruence between appropriation and provision rules and local conditions
- collective-choice arrangements
- accountable monitoring
- graduated sanctions
- conflict-resolution mechanisms
- minimal recognition of rights to organize
- nested enterprises

Subsequent research has found that the design principles are correlated with successfully[8] managed Couple Infrastructure Systems (CISs), but it has not shown that all of the eight are always present in successful cases: sometimes a subset of the eight design principles is present, and the subset does not always consist of the same principles (Cox et al., 2010; Baggio et al., 2016). Moreover, they show that these results are idiosyncratic, and that they depend on how specific biophysical and ethnographic characteristics may impact in the performance of CIS governance. Some other case studies like Quinn et al. (2007) and Morrow and Hull (1996) corroborate the need to find context specific variables that may affect CIS management. *I hypothesize that the set of design principles that are necessary and/or sufficient for successful management depends on the social and biophysical characteristics of the system.*

Although Ostrom, in her work on the design principles, focused mainly on institutional features combined with other social components associated with success, she did acknowledge that it is the interaction among social, institutional, and biophysical components that determines success (Ostrom, 1990). Ostrom explicitly stated that further research should examine all of these components together (Ostrom, 2000); however, she did not have the time to do that research herself. My study responds to her call. For this paper, my research question is: *For given biophysical and ethnographic characteristics (typologies) of a CIS, which institutional design principles are necessary and/or sufficient*

[8] The authors considered cases as "successful" differently: for Cox et al. (2010) it was left to the original authors reports on long-term environmental management; and for Baggio et al. (2015) it is defined as cases "that have not displayed ecological deterioration (i.e. resource sustainability), nor conflict and trust issues according to the secondary data sources at our disposal" (Baggio et al. 2015, p.3)

to avoid over-appropriation, poverty and critical conflicts among users of an irrigation system[9]?

In the following section, I describe the method that was used in detail. Since meta-analysis is a relatively new method for the study of CISs, I describe the steps I follow in order to contribute to the development of meta-analysis as a method. 37 conditions (i.e. causal variables) were selected for the analysis, and 4 as outcome variables that were later combined into a fuzzy variable labeled as "fuzzySuccess". I describe the procedure that helped to narrow down the 37 variables to 8 conditions in order to be able to proceed with the analysis. With the help of the fs/QCA software the information of coded cases are processed to find the shortest possible logical expression and study necessity and sufficiency. I found that particular combinations of those variables related to population size, countries corruption, the condition of water storage, monitoring of users behavior, and involving users in the decision making process for commons governance, were sufficient to obtain the desired outcomes.

Method: Meta-analysis of 28 Irrigation Systems around the world

Meta-analysis is the analysis of analyses (Poteete et al., 2010). Meta-analysis codes data from many different studies to reveal patterns so that generalizations can be derived from a group of discrete studies (Rudel, 2008). Meta-analysis can advance understanding of collective action in Coupled Infrastructure Systems (CISs) by identifying commonalities and patterns of collective action in different systems. With

[9] For this analysis I have differentiated the design principle components described in the previous chapter.

this information, we can then hypothesize about sources of variation in system outcomes (Rudel, 2008; Poteete et al., 2010). Meta-analysis complements the case-study method, which collects and analyzes primary data within narrow boundaries of space and time.

A limitation of meta-analysis is that it relies on secondary data, so the validity of the analysis depends on the quantity and quality of the studies chosen for analysis. This limitation becomes especially problematic when the studies available for analysis have looked at different variables and/or do not include all of the variables that the researcher wants to test (Rudel, 2008; Poteete et al., 2010). For this reason I have selected among cases that used in their research variables included in the Institutional Analysis and Development Framework (IAD) (Ostrom, 1990), or the Socio-Ecological Systems Framework (SES) (Ostrom, 2009). These two frameworks were designed to (among other purposes) organize data in a way that makes meta-analysis possible (Ostrom, 2011). For those cases that are missing data in the original source, I have used other studies of the same cases as proposed by Poteete et al. (2010).

Meta-analysis is a relatively new method for the study of CISs; the way it is used needs further refinement. Therefore, my meta-analysis will be neither definitive (Poteete et al., 2010), nor representative of all irrigation systems. But it will contribute to our knowledge of patterns of interaction between the biophysical and social components of Coupled Infrastructure Systems and how those patterns may affect system sustainability. In the following section, I describe the steps I follow in order to contribute to the development of meta-analysis as a method, as well as to make the research replicable[10].

Meta-Analysis procedure. To be credible, a meta-analysis must meet the challenges that arise in variable selection, case-study selection, coding procedures, and conjoint causation (Rudel, 2008).

Variable selection. In this study, information was processed from the case studies according to a set of selected variables. This type of meta-analysis is known as Model Centered Meta-Analysis, were patterns according to conceptual models that are developed from previous studies were targeted (Rudel, 2008). The first group comprises four outcome variables. Outcome variables whether the resource was over-appropriated in the system, where there was environmental degradation in the system (e.g. water pollution, or deforestation caused by agriculture activity), if there are critical conflicts among water users, and whether or not users agricultural activities have productive outcomes (absence of poverty).

The variables that were expected to influence the outcome variables were divided in two categories: remote and proximate factors, as suggested by Schneider and Wageman (2006). Both types of variables are expected to be causal in relation to the analyzed outcomes, but remote factors are relatively stable over time. These factors are what are referred to in the commons literature as "contextual" factors that are labeled as "biophysical" and "attributes of the community" in the IAD framework Ostrom (1990, 2005, 2011). The proximate factors vary more often over time, do not originate far in the past, and are the result of actions of human agency (including actors' actions). Thus, the

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[10] Replicability makes it possible for other researchers to corroborate or falsify the research findings, which is an important condition for progress in scientific knowledge (Popper, 2014).

components of the design principles (institutional variables) are included in this analysis as proximate factors. I believe that this distinction is important not only for the procedure of analysis that I explain later, but also for the differentiation of variables that are easier than others to influence for policymaking.

Table 3.1 shows the remote or contextual variables selected, and the authors of the studies that suggest them as variables related to successfully managed CISs. Table 3.2 shows the components of the design principles identified in the previous chapter.

It is important to reiterate that I analyze how these variables, *in conjunction with one another*, affect collective action (as suggested by Agrawal 2002). A variable can affect collective action in various ways depending on the other contextual variables that are present in the system. For example, consider the variable "size of the resource system". One can assume that the smaller the system, the easier it is to monitor farmers' water use (Janssen & Anderies, 2013) and to come to an agreement for collective action (Wade, 1987). However, the size effect may be offset by the degree of heterogeneity or asymmetry of user conditions, as in CISs with upstream-downstream users, different crop water demands, different individual plot sizes, etc. (Ostrom et al., 1994; Adger 2003).

The variable listed were selected and modified in an iterative fashion. I started with a high number of variables to systematically capture cases knowledge, however this can cause a problem of uniqueness (too many variables that make the case one of a kind) with high complexity and no parsimony, and a low number of variables can generate more data contradictions (Rudel, 2008). The number of variables to be analyzed was lated reduced, as I exaplain explained below.

Table 3.1

Contextual Variables

Variable Name	Variable Description	Source
Gwater	Type of Water Source	Schlager et al. (1994), Ostrom et al. (1994)
Asymm	Asymmetry	Ostrom et al. (1994)
NGOs	Presence of NGOs	McGinis & Ostrom (2014)
Perturbation	Perturbations in the CIS	Glance & Huberman (1994)
Envpert	Environmental Perturbations in the CIS	Glance & Huberman(1994)
freqpert	Frequency of Environmental Perturbations	Glance & Huberman(1994)
Wpredic	Weather Predictibility	Wade (1988)
corrup	Country Level of Corruption	Berkes (2002); Young (2002)
Visib	System's Visibility	Trawick (2001)
pdinfo	Rule Compliance Information	Schlager, Blomquist, and Tang (1994)
SelfSust	Self-Sufficient	Ostrom (1990)
Subs	Governmental Help	McGinis & Ostrom (2014)
Irrigdep	Irrigation Dependance (complemented with rain)	Gibson (2001)
commond	Type of Crop grown (commodity or not)	Pinkerton & Weinstein (1995), Gibson (2001), Wade(1988) , McCarthy et al. (2001)
Agdepend	Farming for Susbsitance or for Commercial purposes	Gibson (2001), Pinkerton & Weinstein (1995), Gibson (2001)
Mktintg	Market Integration	Tucker (1999), Tucker et al. (2007), Bardhan (2000) , Klooster (2000) , Cinner & McClanahan (2006)
cropwdem	Crop Water Demand	Wade (1988)
Tech	Irrigation Technique	Wade (1988)
exppubinf	Public Infrastructure Maintenance Fee	McCarthy et al. (2001), Abbot & Wilen (2010)
Fair	Sense of Fairness	Wade (1988)
Popsize	Population Size	Agrawal (2002), Baland & Platteau (1996)
Homog	Homogeinity	Baland & Platteau (1996), Adger (2003)
sizephys	System Physical Size	Agrawal (2002), Baland & Platteau (1996)
DistCond	Distribution Infrastructure Condition	Ostrom et al. (1994)
ProdCond	Production Infrastructure Condition	Schlager et al. (1994), Ostrom et al. (1994)
trustothers	Trust in Other Users	Wade (1988)
Trustlead	Trust on Leaders	Wade (1988)

Table 3.2

Design Principle Components Variables

Variable	Design Principle Component
	DP1: Clear Distribution Rules
DP1USERS	Clearly defined physical boundaries
DP1Borders	Clearly defined user boundary rules
CManager (Not included because of Limited Variability)	Clearly defined manager
Cexclude (Not included because of Missing Information)	Clearly defined who can exclude others from the system
Bccongr	Clearly defined appropriation rules
Bccongr	Clearly defined provisioning rules
Bccongr	Conrguence between appropriation and provisioning rules
	DP2: Congruence with Situated Conditions
	This is Partially Captured by the Context Variables
	DP3: Stakeholder Effective Participation
Elect	Users point of view are effectively taken into account
Knowledge (Not included because of Limited Variability)	Other relevant non-users' point of view are effectively taken into account.
	DP 4: Monitoring
Monitoring	Presence of a monitoring mechanism of rule compliance
Maccount	Monitoring mechanisms are accountable
pdinfo	Users know the level of rule compliance
RecCondSES	Monitoring of the ecological condition
RecCondSES	Monitoring of the human-made hard infrastructure
	DP5: Sanctions
SanctEnff	There is a negative consequence for users that do not comply with rules by receiving a type of sanction. 2)
Gradsanc	Graduated sanctions depending on type of infraction, the degree and the frequency.
SanctEnff	Sanctions are effectively enforced
SanctionsKnow (Not included because of Missing Information)	Users know when sanctions are imposed
	DP 6: Conflict Resolution Mechanisms
confres	Different opinions and situations are exposed and considered in order to solve conflicts, which may imply or not, rules modification.
	DP7 Rights to Organize
ColAct	Users have the rights to organize
confres	Users effectively are part of a formal or informal organization that is not undermine by other instance of governance.

	DP8: Proposed modification: Appropriate relations with other tiers of rule-making authority (polycentric governance)
Polycent	Polycentricity

The variables *"defined managers", "presence of appropriation rules", Presence of provision rules", "non users presence", "users are part of an organization",* had limited variability and were not included in the analysis because of this reason. We could infer that these variables are necessary – though not sufficient- for a desired outcome, but this conclusion may be trivial given that I did not find cases (or too few cases) that show what happens if these variables are not present. It is, however, worth noting this finding for future research. Also, to reduce concept misinterpretation for coding understanding, it is preferable to have precise definitions of variables, which is more likely to happen when the concepts of the variables are refined after coding a smaller sample of cases (Glaser & Strauss, 1967).

Case-study selection. Even though there is no agreement among researchers about which is the best strategy for selecting cases, any good strategy must *control bias*, ensure *compatibility*, and maximize *variation* (Rudel, 2008). *Bias* can be caused by differences in study quality, closely correlated studies (interdependent), and publication bias (Poteete et al., 2010). To minimize bias:

- Only cases in which place names and dates of fieldwork are mentioned were included, and duplication of analysis of the same observation was avoided in order to recognize interdependence
- Unpublished case studies, studies published in prominent journals, and studies published in less-prominent journals were selected to reduce publication bias

Even with these controls, sample bias is only reduced, not eliminated entirely. Appendix A shows the list of cases that were studied and the references as secondary data. I have chosen cases that have a CIS as a unit of analysis and that have similar research questions to the question: "What are the factors that influence the outcome of irrigation-system governance?" By using these two filters, I ensure comparability among the cases as suggested by Rudel (2008). To ensure variability of cases, I have chosen cases from different regions of the world as shown in Rihoux & Ragin (2008)

It is critical that comparable cases possess diversity with regard to the variables that will be included in the model. The studies have enough variability (at least one third of possible results) with respect to the variables and outcomes defined for the research as suggested by Rihoux (2006) and Rihoux & Ragin (2008)

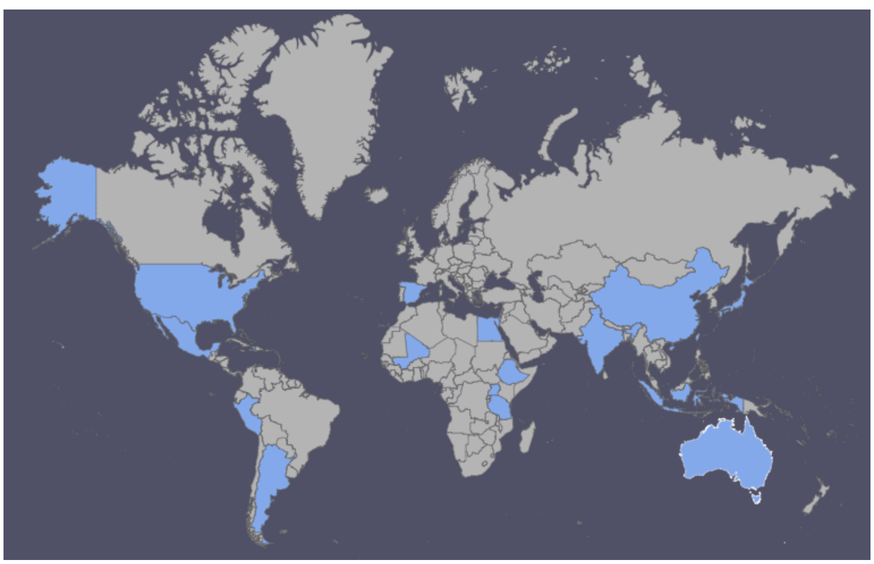

Figure 3.1: Countries of Cases Included in the Analysis. List of Countries of Case Studies: Argentina, Australia (2), China (3), Egypt, Ethiopia (2), Haiti, India, Indonesia, Israel, Japan, Mali, Mexico, Peru (3), Philippines, Spain (2), Taiwan, Tanzania (3), Uganda, USA.

Coding procedures. I used the coding scheme shown in Appendix B. Case studies and their variable scores are listed in Appendix C to give credibility to the research (Rudel, 2008). As mentioned earlier, the concepts of the variables were refined after coding 10 cases to have as precise as possible definitions of variables and reduce concept misinterpretation for coding understanding.

Conjoint causation. Meta-analysis for CISs does not have an average effect as it does in medical, biological, or psychology studies (the pioneer sciences in meta-analysis), because it analyzes a synthesis of findings instead of numerical values (Rudel, 2008). Because CISs present complex relationships among their variables, we need to use a method of analysis that allows for causal heterogeneity and conjuncture relationships (various conditions at the same time). For these purposes, Qualitative Comparative Analysis (QCA) is a recommended method of data analysis (Rudel, 2008). QCA is a method that reconciles qualitative and quantitative analysis. It systematically sorts the in-depth information from case studies into the smallest sets of factors that, in combination, are consistently associated with a particular condition, thus making it possible to derive generalizations (Ragin, 1987). QCA analyzes patterns to reveal conjoint causal effects directly, which is what is needed to understand what happens in coupled infrastructure systems. Thus, I have chosen to use QCA to analyze the data from the case studies I will use in my research.

QCA uses Boolean algebra[11] to produce a model with logical and holistic representations (Rohwer, 2008). Variables that are not evaluated outcomes are called causal conditions (Rihoux & Ragin, 2008). Some of the selected conditions, as well as

[11] See Ragin (1987) for a detailed explanation of Boolean logic and operations.

the outcomes, were coded as crisp values (dichotomous variables of 0 and 1 of membership of a given case in the variable), and others where coded as fuzzy values (values between 0 and 1 that shows degree of membership instead). Tables 3.3, 3.4 and 3.5 show the calibration used for the fuzzy values[12] and crisp values.

Table 3.3

Outcome Calibration

Outcome	Calibration
Successfz	Average of scores
	No Overappropriation (Y=1, N=0)
	No Critical Conflicts (Y=1, N=0)
	Environmental Degradation (None =0 Some, controlled=0.45 Big problem=1)
	Non Poverty (Y=1, N=0)

Table 3.4

DPs Components Calibration

DPs Components	Calibration	DPs Components	Calibration
DP1USERS	Is it clear who are the users of the resource and their rights are recognized? 1= Yes, 0= No	Monitoring	Does someone monitor the resource appropriation? 1 = Yes, 0 =No
DP1Borders	Are the borders and water sources that the community can use clearly defined? 1 =Yes, 0 = No	Maccount	Users actually believe that they can get caught when getting more of their share 1 =Yes, 0= No
Bccongr	Congruence between appropriation and provision rules 1 =Yes, 0 =No	Gradsanc	Do they have graduated sanctions and this are known by users? Yes = 1, No = 0
Elect	Do users participate to elect their leaders? 1 = Yes, 0 = No	SanctEnff	Users believe that they can get caught and be fairly sanctioned if they do not cooperate? 1 =Yes, 0 =No
RecCondSES	Do they keep records of the water level in the river, reservoir or groundwater? 1 = Yes, 0 = No	Transparency	Do users know management details? 1 =Yes, 0 =No
ColAct	Has there been collective action to change rules? 1 = Yes, 0 = No	Polycent	Appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities are well organized in multiple layers of nested enterprises and they don't conflict with each other? 1 = True, 0 =False
confres	Is there at least one shared space/area for conflict resolution that it is being used? 1 = Yes, 0 =No		

[12]For calibration I follow the suggestions on good practices for calibrating described by Rihoux & Ragin (2008)

Table 3.5

Contextual Conditions Calibration

Conditions	Calibration	Conditions	Calibration
Gwater	1= Users withdraw from groundwater exclusively 0.6 = Users withdra from groundwater but not exclusively 0 = Users withdraw only surface water	cashcrop	Is it mostly subsistance agriculture or cash crops? Cahs only = 1, mixed = 0.5, subsistencia = 0
Asymm	0 = Big degradation problems 0.45 = some deg problems 1= no degradation problems	Agdepend	Farmers dependence on Agriculture high = 1, medium = 0.66, low=0.33
NGOs	Are Non-Governamental Organizations involved? Non-Governamental Organizations involved = 1 Non-Governamental Organizations **NOT** involved = 0	Mktintg	Market integration 1 = Yes, 0 = No
Perturbation	The system was affected by a perturbation = 1 The system was **NOT** affected by a perturbation = 0	cropwdem	High water intesive cros 1=Yes, 0 = No
freqpert	Frequency of environmental perturbation 1 = very often , 0.4 not often, 0 = No perturbation	Tech	1 = dripirrigation, 0.6= sprinkles, 0= furrow
Envpert	Is the system exposed to natural disasters? 1 = yes, 0 = no	exppubinf	Is the public infrastructure expensive to maintain? 1=Yes, 0=no
Wpredic	weather predictability 1 = the weather is very predictable 0.4= weather is somehow difficult to predict 0 = unpredictable	Fair	Do Appropriators think rules are fair? Yes = 1, No = 0
corrupFz	From the Corruption Index of Year of Research. Calibration threshold: 4.5, 3.1, 2.6	Popsize	How many users are there in the system? Calibration thresholds: 10000, 4000, 2000
Visib	Can users see most of other users water appropriation? yes=1, no=0	Homog	Are users homogenous? Yes = 1, No = 0
pdinfo	Users have information about the behavior of other users with regards to public infrastructure provision 1 = yes, 0 = no	sizephys	Size in Ha. Calibration Thresholds: 100000, 10000, 1000
SelfSust	Is the system self-sustained? 1=Yes, 0=No	DistCond	Well mainained = 1, somehow maintained=0.55, poorly maintained = 0
Subs	Do users have governmental support 1= yes more than 1 type 0.8 = subsidies for water use 0.6 = yes only one type 0 = no	ProdCond	Well mainained = 1, somehow maintained=0.55, poorly maintained = 0
Irrigdep	Are crops also watered with rain? rain = 0, no rain = 1	trustothers	Yes = 1, No = 0
commond	Are users growing commodities? 1 = Yes only, 0.6 = yes but also other, 0 = no	Trustlead	Yes = 1, No = 0

With the processed data, it is possible to develop truth tables, which helps to identify whether a propositional expression is logically valid (i.e. if the expression is true for all input values).

QCA reveals regularities in the data by processing the truth table and finding the shortest possible expression (Boolean minimization (Rudel, 2008)). The shortest possible expression reveals the variables that are necessary and/or sufficient for the "success" outcome. QCA makes qualitative data easy to read by expressing it quantitatively. Data expressed numerically can be processed more consistently than data expressed in words. It is possible to process large datasets when it is expressed as numbers and, at the same time, quantitative data is easily manually processed.

Unlike other quantitative approaches, QCA captures information from deviant cases by considering contrafactuals, and allows for an iterative process of analysis that helps the researcher explore the reasons for apparently contradictory outcomes (Rudel, 2008). Moreover, several researchers have concluded that QCA yields more knowledge from the same data than other kinds of analysis (e.g. discriminant analysis, multiple regressions, factor analysis) when more than one condition is in play (Berg-Schlosser & De Meur, 1997; Berg-Schlosser & Cronqvist, 2005; Amenta & Poulsen, 1996; Ebbinghaus & Visser, 1998; Nelson et al., 2005; Amoroso & Ragin, 1999; Ragin & Bradshaw, 1991)

Results

The data along with the cases coded shown in Appendix C was imported to the fsQCA software[13] (for descriptive statistics of the coded variables see Appendix D[14]). Because fsQCA is not exempted from the "too many variables and too few data" problem

[13] April 2017 version (www.fsqca.com)

[14] From the coded data I found that the variables that were more neglected in the studies are: rule compliance (21%), if users pay water fees (21%), transparency of management (32%), visibility of appropriation 25%, type of technology used to irrigate (30%), predictability of the weather (25%), environmental perturbations (43%), land condition (61%), homogeneity of users (25%), if the population is growing (39%), education level (79%), users knowledge of farming practices (71%), Information shared with users about public infrastructure provisioning (32%) and market integration (25%).

faced by any other methods, I follow the strategy suggested by Schneider and Wagemann (2006) to include in the analysis the variables that are shown to have more impact on the outcome.

First, using coincidence analysis[15], I look separately at the relationship between each contextual variable and DP components with the outcome variable "successfz" (see tables 7 and 8). From this analysis I ranked the variables that had more coincidence with the outcome and select them (highlighted with "*" in the table) for the next step of the analysis. I also made sure to check for the coincidence with a low membership of each variable with the outcome to see the relationship when inversed. As we can see in table 8 for example, the number of users in a system coincides with successful outcomes when it is small, but not when it has a higher value. Notice that the condition NGO was not selected. This decision was made based on case studies knowledge. It seems that NGOs are present in a system (e.g. NGOs decide to work in a specific system because there is a sustainability problem perceived) when there are environmental or social problems, thus it is not accurate to assume that the presence of NGOs are causal conditions.

[15] Coincidence analysis shows the percentage of cases on which the outcome is present and a condition is also present.

Table 3.6

Coincidence Analysis: Success and Contextual Conditions

Condition	SuccesFz	
	Present	Absent
*corrupFz	0.58	0.4
*ProdCond	0.56	0.3
*cashcrop	0.56	0.13
*Agdepend	0.55	0.14
*Wpredic	0.54	0.35
*SelfSust	0.53	0.22
*Mktintg	0.52	0.23
commond	0.49	0.4
Fair	0.49	0.32
Subs	0.47	0.41
Envpert	0.44	0.07
Asymm	0.44	0.31
sizephys	0.43	0.53
Irrigdep	0.43	0.36
trustothers	0.43	0.34
freqpert	0.42	0.15
Perturbation	0.41	0.36
cropwdem	0.41	0.36
Trustlead	0.41	0.34
DistCond	0.35	0.47
Visib	0.35	0.43
Tech	0.34	0.41
Gwater	0.32	0.48
exppubinf	0.3	0.47
Homog	0.27	0.43
*PopsizeFz	0.24	0.6
NGOs	0.14	0.62

Table 3.7

Coincidence Analysis: Success and DPs Components

DPs Components	SuccesFz	
	Present	Absent
*pdinfo	0.7	0.08
*confres	0.63	0.11
*DP1USERS	0.6	0.16
*RecCondSES	0.6	0.16
*Monitoring	0.58	0.17
*ColAct	0.57	0.16
*Polycent	0.53	0.26
*Elect	0.53	0.22
Transparency	0.49	0.33
Bccongr	0.48	0.3
Maccount	0.48	0.29
DP1Borders	0.47	0.3
SanctEnff	0.37	0.41
Gradsanc	0.36	0.42

However, since “Cashcrop”, and “Mktintg” are theoretically similar, and the coincidence between them is 0.83. It is possible to use only one of them. Therefore, for the next analysis I drop “chascrop” and leave “Mktintg” since this last has less missing values. Also, although “pdinfo” has a high level of coincidence with successful cases, it has a 35% incidence of missing data. Its inclusion in the analysis so far had the purpose of showing that this variable is not considered in the literature of the commons and yet, it seems that it might have an important role to play for generating desired outcomes. However, the high number of missing values of "pdinfo" can be problematic for the next steps of the analysis. Hence, I drop this variable from the analysis.

Also, it is important to mention that the exclusion of the analysis of these variables is not because these variables are not relevant to the outcome. As we can see in tables 6 and 7, for many of the variables analyzed there is more coincidence with the outcome when they are present than when they are not present, which is consistent with the literature. I just proceed to analyze the ones that show a stronger relationship with the outcome for the feasibility of the analysis, but there are always some limitations resulting from not including in the analysis every potential variable theoretically based. This is not however possible with any available method, yet.

As a second step, I analyzed separately how the contextual variables and the DPs components, in conjunction, relate to the outcome variable "Successfz".

Table 3.8 shows all possible combinations of contextual variables that present a level of consistency above 0.8. For the next step of analysis, I chose those variables that are included in the recipes that have the highest coverage. Coverage expresses how much of the outcome is covered or explained by the conjoint causal conditions, or as called by Ragin (2008) "recipes". The variables that were selected according to these criteria are: "corrupFz", "ProdCond", "Agdepend", and "~popsize"[16]

[16] ~popsizefz is the negation of big size population. Then it can be interpreted as the membership of a case in the criteria "small size population"

Table 3.8.

Subset / Superset Analysis: Success and Contextual Variables

Recipes / Paths	consistency	coverage
corrupfz*ProdCond	0.863351	0.686988
ProdCond*Agdepend	0.815217	0.66845
corrupfz*ProdCond*Agdepend	0.859835	0.667023
~popsizefz*corrupfz	0.883687	0.652763
~popsizefz*corrupfz*ProdCond	0.885458	0.633868
~popsizefz*corrupfz*Agdepend	0.880456	0.632799
~popsizefz*ProdCond*Agdepend	0.833012	0.61533
~popsizefz*corrupfz*ProdCond*Agdepend	0.882172	0.613904
corrupfz*ProdCond*Mktintg	0.842459	0.581462
corrupfz*ProdCond*Mktintg*Agdepend	0.837766	0.561498
ProdCond*Mktintg*Agdepend	0.828947	0.561498
~popsizefz*corrupfz*Mktintg	0.863688	0.544385
corrupfz*ProdCond*SelfSust	0.833515	0.544385
~popsizefz*corrupfz*ProdCond*Mktintg	0.865654	0.528342
~popsizefz*corrupfz*Mktintg*Agdepend	0.859229	0.524421
corrupfz*ProdCond*Agdepend*SelfSust	0.828266	0.524421
~popsizefz*corrupfz*SelfSust	0.856205	0.511587
~popsizefz*corrupfz*ProdCond*Mktintg*Agdepend	0.861111	0.508378
~popsizefz*ProdCond*Mktintg*Agdepend	0.850835	0.508378
ProdCond*Wpredic	0.839286	0.502674

Table 3.9 shows different recipes when considering only DPs components, and it is ranked from better fit to less. Following the same criteria of the contextual variables analysis, the selected DPs components to be analyzed on the next step are: “Monitoring”, “confres”, “Elect”, and “Polycent”

Table 3.9.

Subset / Superset Analysis: Success and DPs Components

Recipes / Paths	consistency	coverage
confres*Monitoring*Elect	0.806818	0.57583
confres*Monitoring*Polycent	0.8125	0.47445
Monitoring*Polycent	0.8125	0.47445
DP1USERS*confres*Monitoring*Elect	0.806944	0.47121
confres*Monitoring*Polycent*Elect	0.866071	0.39335
Monitoring*Polycent*Elect	0.866071	0.39335
confres*RecCondSES*Monitoring*Polycent*Elect	0.84375	0.32847
DP1USERS*confres*Monitoring*Polycent*Elect	0.84375	0.32847
confres*Monitoring*ColAct*Polycent*Elect	0.84375	0.32847
RecCondSES*Monitoring*Polycent*Elect	0.84375	0.32847
DP1USERS*Monitoring*Polycent*Elect	0.84375	0.32847
Monitoring*ColAct*Polycent*Elect	0.84375	0.32847
DP1USERS*confres*RecCondSES*Monitoring*Polycent*Ele	0.8125	0.26359
confres*RecCondSES*Monitoring*ColAct*Polycent*Elect	0.8125	0.26359
DP1USERS*confres*Monitoring*ColAct*Polycent*Elect	0.8125	0.26359

With only 8 conditions (256 potential configurations), the problem of limited diversity is not solved with only 28 cases, but at least it has been reduced. The next step is to do a subset – superset analysis but this time with the two types of conditions (remote and proximate) together. The combination of variables that show a higher consistency of at least 0.8 and that explain the outcome to a greater extent are (see table 10): Confres, Prodcond, ~popsizefz, Monitoring and Corrupfz.

Table 3.10.

Subset / Superset Analysis: Success and Selected Conditions

Recipes / Paths	consistency	coverage
~popsizefz*Monitoring	0.875767	0.728162
Monitoring*confres	0.8225	0.699256
~popsizefz*Monitoring*confres	0.889079	0.6644
ProdCond	0.875723	0.643996
Monitoring*Elect	0.802778	0.61424
Monitoring*confres*Elect	0.871875	0.592986
~popsizefz*Monitoring*confres*Elect	0.87484	0.579384
~popsizefz*Monitoring*Elect	0.87484	0.579384
ProdCond*~popsizefz	0.885144	0.57492
~popsizefz*confres*Polycent	0.820849	0.55898
~popsizefz*Polycent	0.820849	0.55898
ProdCond*confres	0.910211	0.549416
Monitoring*corrupfz	0.858757	0.516897
ProdCond*Monitoring	0.923664	0.514347
ProdCond*~popsizefz*confres	0.904135	0.511159
ProdCond*corrupfz	0.912614	0.510521
ProdCond*~popsizefz*Monitoring	0.923318	0.501594
~popsizefz*corrupfz	0.934127	0.500319

With only 5 conditions, it is possible now to analyze a truth table. Because we are including fuzzy sets, I used the fuzzy set algorithm developed by Ragin (2008). Table 11 shows the truth table using the selected conditions. In column "Consistency" it is shown the consistency value running from 0 to 1 (where values higher tan 0.8 are considered consistent). In column "N", we can see the number of cases that have a membership in the respective causal combination higher than 0.5. The column "SuccesFz" indicates for each causal combination whether it passes the test criteria for 'very often sufficient'[17] and whether it contains enough cases[18]. If these two conditions are fulfilled, the conjunction passes the test, meaning that it is a sufficient condition for "SuccessFz". In essence, the column "SuccessFz" indicates which of the causal combinations produce the outcome (1,

[17] I chose a threshold of 0.8 of consistency, which implies that at least 80% of the cases' membership scores in the combination must be consistent.
[18] I chose a threshold of at least 1 case with higher membership 0f 0.5

rows 1–6, 13 cases), and which ones do not (0, rows 7–14, 14 cases), as well as which combinations have no empirical instances (rows 15–64).

Table 3.11

Truth Table

Configuration	Conditions					N	SuccesFz	Consistancy
	Confres	Monitoring	PopSizeFz	CorrupFz	ProdCond			
1	1	0	1	0	1	1	1	1
2	1	0	1	0	0	1	1	0.94
3	1	1	0	0	1	1	1	0.86
4	1	1	1	1	1	1	1	1
5	0	1	0	1	1	1	1	1
6	1	1	0	1	1	8	1	0.95
7	1	1	0	0	0	4	0	0.79
8	0	1	0	0	1	1	0	0.49
9	0	1	1	0	0	2	0	0.3
10	1	0	0	0	0	2	0	0.3
11	1	0	0	1	1	2	0	0.75
12	1	1	1	1	0	1	0	0.66
13	0	0	1	1	1	1	0	0.66
14	0	1	1	1	0	1	0	0.58
…						0	?	
64						0	?	

Table 11 shows the truth table in a dichotomous (crisp set) fashion. However, the more fine-grained fuzzy information on the 28 cases is not lost and it is used in the following analytical steps. The 28 cases are organized into 14, but there were 64 logically possible combinations. This implies that there are 36 logical remainders (combinations for which empirical evidence is lacking (rows 15–64)). This is called limited diversity (Ragin, 2008), and it is common in comparative social science (Schneider and Wagemann, 2006). However, with QCA it is possible to make it transparent, and treat it, which other methods seem to fail at doing (Ragin, 2008). In fs/QCA, the researcher is forced to make conscious simplifying assumptions based on case and theoretical knowledge.

I use the Quine-McClusky algorithm for dichotomous data (Ragin 1987) in which the rows with the outcome value 1 are set to 'true' and the 0 outcomes are set to 'false' and the logical remainders are set to the theoretical expectation: we expect to have more cases successful when the design principle components "Confres" (Users participate in decision making and conflict resolution mechanism), and "Monitoring" (The appropriation of the resource is monitored) are present, and when the population is small. For CorruptionFz (membership in low corruption country) and ProdCond (Reservoir Condition) I set "do not care" because we do not have consistent evidence to assume either relation. These assumptions help to identify the intermediate solution, which considers in the logical reminder only those combinations that are coupled with the assumption. In the parsimonious solution, we can see what happens if we let the computer induce all possible (even thsoe not coupled with theory), and in the complex solution, we find recipes that only use empirical data (Ragin 2008).

Table 3.12:

Complex, Intermediate and Parsimonious Solutions

	SuccessFz =	Context Conditions	DP Components	Consistency	N	Cases	Coverage
Complex Solution Consistency = 0.91 Coverage = 0.59	(R1)	PopSizeFz * ~LowCorrupFZ	Confres*~Monitoring	0.95	2	Usangu, Niger	0.09
	(R2)	~PopSizeFz * ProdCond	Confres*Monitoring	0.88	9	ZhuoluSGSW, AlBayda, Murray, Dubre, ZhuoluSGSAGW, Naomi, Hefer, Chianan, SanJuan	0.39
	(R3)	~PopSizeFz * ProdCond * CorrupFz	Monitoring	0.96	9	Murray, Naomi, Hefer, ZhuoluSGSW, SZhuolu, ZhuoluSGSAGW, Chianan, SanJuan, AlBayda	0.36
	(R4)	ProdCond * LowCorrupFz	Confres*Monitoring	0.96	9	Naomi, Murray, Hefer, Nishikambara, ZhuoluSGSW, ZhuoluSGSAGW, Chianan, SanJuan, AlBayda	0.38
	SuccessFz =	Context Conditions	DP Components	Consistency	N	Cases	Coverage
Intermediate Solution Consistency = 0.91 Coverage = 0.64	(R1)	PopSizeFz*~LowCorrupFZ	Confres	0.95	2	Usangu, Niger	0.14
	(R2)	ProdCond	Confres*Monitoring	0.89	10	ZhuoluSGSW, AlBayda, Naomi, Murray, Hefer, Dubre, ZhuoluSGSAGW, Nishikambara, Chianan, SanJuan	0.45
	(R3)	~PopSizeFz * ProdCond *LowCorrupFz	Monitoring	0.96	10	Murray , Naomi, Hefer, ZhuoluSGSW, Szhuolu, ZhuoluSGSAGW, Chianan, San Juan, AlBayda	0.36
	SuccessFz =	Context Conditions	DP Components	Consistency	N	Cases	Coverage
Parsimonious Solution Consistency = 0.94 Coverage = 0.61	(R1)	PopSizeFz * ~LowCorrupFz	Confres	0.95	2	Usangu, Niger	0.14
	(R3)	ProdCond*~LowCorrupFZ	Confres	0.88	2	Dubre, Niger	0.14
	(R2)	ProdCond * LowCorrupFz	Monitoring	0.96	10	Naomi, Murray, Hefer, Nishikambara, ZhuoluSGSW, Szhuolu, ZhuoluSGSAGW, Chianan, SanJuan, AlBayda,	0.42

Table 3.12 provides a summary of all sufficient conjunctions between context conditions and institutional configurations (recipes) that lead to SuccessFz, for the complex, the intermediate and the parsimonious solutions. As we can see, the intermediate solution is bounded by the parsimonious and complex solutions. In this case, the parsimonious solution is preferred because it includes simulations for all possible configurations, including for the logical reminders, and its results do not contradict theoretical and case based knowledge. Moreover, in this case the parsimonious is just a simplified version of the complex solution, which means, that it is well coupled with the empirical data.

All 3 paths (4 paths in the complex solution) display a consistency value higher than 0.8 and in all of them at least one case has a membership higher than 0.5. Thus, the results obtained fulfill the sufficiency criteria established at the outset of the analysis. The parsimonious solution can be read as follow:

In order to achieve a more successful outcome when managing a CIS, the design principle component that is more critical depends mainly on two characteristics of the system:

1) If the population size of the CIS is bigger, and the corruption level of the country on which the CIS is located is high, then users need to be part of the decision making process for the commons governance with well enforced conflict mechanisms.

2) If the reservoir and/or other water storage of the CIS is in good condition, but the corruption levels of the country on which the CIS is located is high, then users need to be part of the decision making process for the commons governance with well enforced conflict mechanisms.

3) If the reservoir and/or other water storage of the CIS is in good condition and the corruption level of the country on which the CIS is located is low, then with only monitoring is sufficient in other to get desired outcomes.

Discussion and Conclusion

It is not possible to generalize the results of this study given the limitations mentioned above (number of case studies analyzed with respect total real CIS, number of contextual conditions and institutional aspects to consider, some selection bias impossible to eliminate, the need of coding revision by other coders to reduce coding mistakes, presence of missing data, among others). However, this work is one small step forward for theory building of the commons.

We have learned from this study which are the variables that were neglected in the selected case studies. Most of them are ethnographic characteristics like education level, or rule compliance. Some others are more related to farming practices such as the technology used to irrigate, farming knowledge, while others related to biophysical characteristics such as land conditions, and weather predictability.

With the coincidence analysis we learned that there are variables that, when present, enhance the chances that governance will be more successful than when absent. For the design principles this was true for all but graduated sanctions and sanction enforcement. It might be because of the poor fit between sanction rules and users payoffs. In the Japanese irrigation system for example, there was no need to enforce sanctions because, for them, non-compliance was an embarrassment that was very difficult to deal with; hence no one wanted to get caught no matter what the sanction was. In this case the real sanction is "embarrassment". For contextual conditions, the most notable ones are (positive relation): low level of corruption, dependence on agriculture, weather predictability, no suppor from the government, high market integration, presence of environmental perturbation, among others.

I show here also how QCA can be a powerful method for theory building. It overcomes the limitations of oversimplification related to correlational methods, and it makes evident and treats limited diversity found in complex systems as irrigation systems. Moreover, it is based on theoretical knowledge and deep understanding of the cases. The outcome of the fs/QCA analysis corresponds to the widely shared common view that we should design institutions for commons governance based on the context, and that the contextual factor influences the outcomes of commons governance. It also shows how these factor matters in conjunction with other conditions. This means that combinations of factors jointly produce the success of the governance in a CIS, not single variables in isolation. This supports the principle of *equifinality*: in open systems, as CIS, different conjunctions can lead to the same outcome (Von Bertalanffy, 1968), or put in other words *"there are no panaceas"* Ostrom (2007).

The results are neither definitive nor generalizable, but nonetheless can be useful for policymakers when financial resources for managing a CIS are scarce and decisions have to me made among many intervention options–as is generally the case. Future research can explore this method with different cases to compare the results using similar variables and similar outcome definitions. It can also be used for different types of CIS such as fisheries, forests, etc. or with other sets of irrigation systems.

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CHAPTER 4

INTEGRATING COLLAPSE THEORIES TO UNDERSTAND ROBUST DESIGNS FOR COUPLED INFRASTRUCTURE-SYSTEMS GOVERNANCE

Introduction

If we look at history, we find that civilizations are built around water sources and land resources that make agriculture is possible. Mesopotamia, Egypt, China, the Indus Valley, Andean South America, and central Mexico are some examples (Lucero, 2002). This is not surprising, since it was agriculture that made placed-based societies possible. It seems though that ever since then – and most likely even before that – solutions to problems generate new challenges. Following this line of thought, we can imagine our ancestors when they discovered agriculture asking themselves how to increase water availability and stability to feed the growing population that was a product of the now stable food source, and so on in a vicious cycle (Tainter, 1988). From this example we can easily perceive the robustness-fragility tradeoffs inherent in securing the most basic needs of societies: food and water. History reflects how, in different cultures, human curiosity, intelligence, and imagination have been enough to overcome these challenges and build different irrigation infrastructures and the rules to govern them, not only to manage the valuable resource, but also for the larger population to avoid destructive internal conflict.

However, we have also observed that many civilizations that were unable to overcome challenges, and collapsed. Something clearly went wrong in the cases of Easter Island and the Mayan civilization, and more recently in the Peruvian town “Santiago

Miraflores de Saña," when a disastrous flood forced survivors to abandon everything in 1728 (Negro and Amorós, 2015). But what happened? Many scholars have studied these and other past civilizations, trying to explain what caused their collapse, and many theories have been proposed. Tainter (1988), for example, suggests that as societies mature, institutions and hard infrastructure become so complex and rigid that they become extremely vulnerable to shocks. When a civilization reaches that point, it becomes unable to withstand a disturbance of any type (environmental, social, institutional, etc.), and the population either disappears or migrates out of the system. Brunk (2002) agrees with Tainter's theory, and argues that in societies that are more and more interconnected, cascade effects of collapses may occur. Tainter and Brunk may be right, but since this theory is somehow pessimistic, leaving us with little else than to just try to delay the collapse of systems, it is worth exploring other possible explanations.

Another group of scholars (Culbert 1973, 1988; Redman 2004, 2005) argues that a major cause of collapse, is as Malthus theorized, the "*overshoot effect,*" in which case a large population demands more than the available resources in a system. As a result, people either migrate to another system, or perish. The overshoot effect is also considered in the "release" phase of adaptive-cycle explanations (Holling, 2001) from resilience theory. Combined with the overshoot effect, Pezzey and Anderies (2003) propose that culturally defined subsistence needs affect the process of collapse due to the overshoot effect . They argue that it is not only the population-resources ratio, but also, and most importantly, how many resources the population thinks it needs to consume (and thus does consume) that determines the "release" or "overshoot" point. Marxist scholars (Gray 2008, Woods 2009), on the other hand, stress the relevance of societies' perceptions of equity, arguing that class conflicts can create internal disturbances that weaken the system as a whole. Diamond (2005) looked at 15 systems that collapsed and some others that did not. He found some commonalities in the cases that collapsed, and brought to the conversation more proposed causes of collapse: failure to anticipate or perceive the problem, elites that were benefiting most from the system opposed change at the expense of society, attachment to values that were detrimental to the ecological environment, and physical (technological or ecological) constraints on people adaptation to a new circumstance.

But why is it important to talk about causes of collapse? The world is facing new environmental challenges that may trigger the collapse of some CIS (Young et al., 2006). The IPCC (2014) has forecasted that more extreme weather events, like heat waves, droughts, floods, and violent storms, may be much more common in the decades to come due to climate change. Although we have an idea of what climatic events to expect in each region, we know less about how CIS can cope with these challenges (Field et al., 2014). The aim of this study is to leverage collapse theories to analyze the robustness of CIS to environmental disturbances, using a case study of the Peruvian Piura Basin, which has been exposed to harsh environmental events associated with the El Niño Southern Oscillation (ENSO). I address here the research questions: *how did the Piura Basin react to El Niño disturbances of 1982/1983 and 1997/1998, why did it react the way it did, and how are actors in the system preparing themselves for future events.*

I consider a CIS to be *robust* if *"it prevents the ecological systems upon which it relies from moving into a new domain of attraction that cannot support a human population, or that will induce a transition that causes long-term human suffering"*

(Anderies et al., 2004 p. 18). A robust system does not necessarily perform at its maximum potential (Csete & Doyle, 2002), but it does remain functional despite internal (e.g., population growth) or external (e.g., droughts) perturbations. For robustness analysis, we need to be explicit about specific perturbations, because systems face tradeoffs between robustness to particular expected disturbances and uncertain fragilities to others (Janssen & Anderies, 2013). Because robustness incorporates a normative component (e.g., the sustainability of a system) related to strategies to achieve an outcome, it is a useful concept to keep in mind when designing institutions. Resilience, a concept related to robustness, also considers the reaction of a system to perturbations, but in terms of endogenous processes within a CIS only, and does not address the question of conscious design (Janssen & Anderies, 2013, Anderies et al. 2004).

The challenge of CIS robustness research is the absence of a developed related theory. Even though, from a logical standpoint, it is not possible to guarantee the robustness of a system by only considering the absence of the causes of collapse, there is an overlap between both outcomes that is worth exploring. In this sense, although the questions I pose are related to the robustness of a CIS to future environmental events, they imply the aim to avoid CIS collapse, and thus collapse theories can provide helpful guidance.

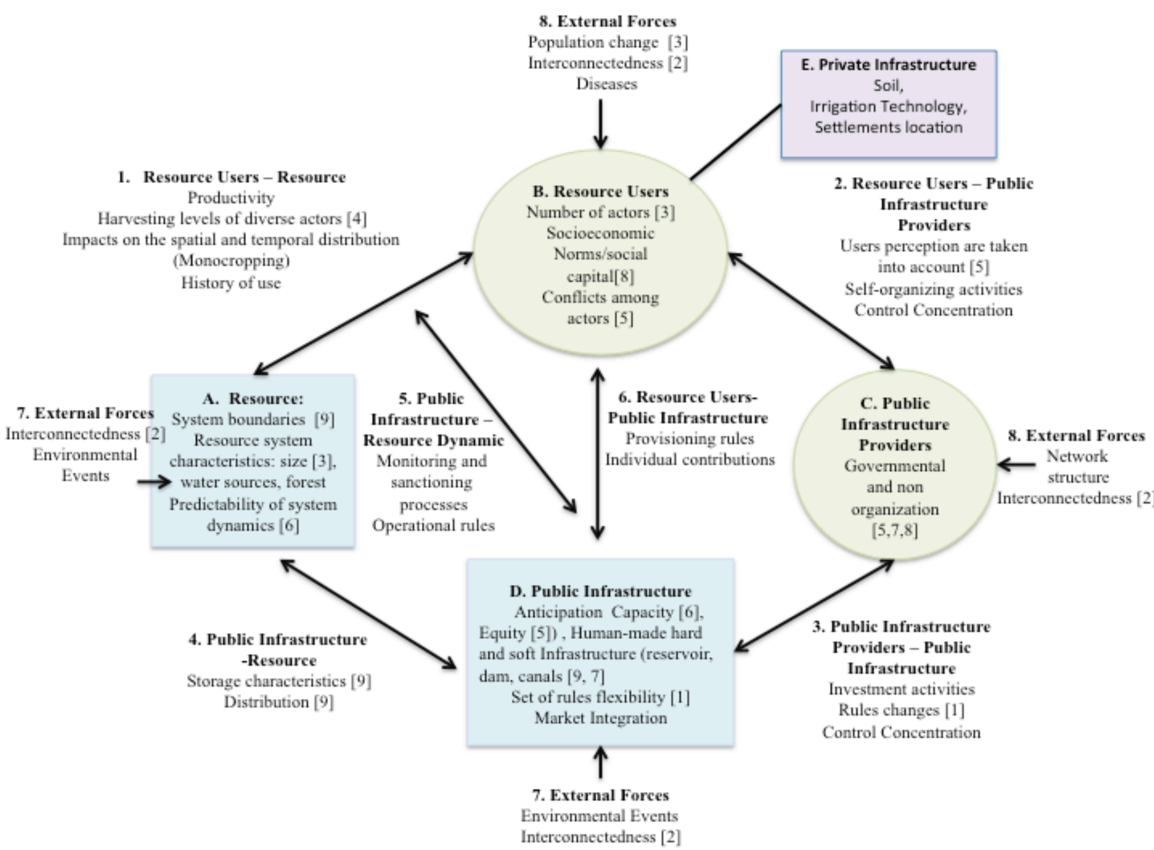
Before going into detail about the Piura Basin, I explain in the next section how I followed the guidelines for carrying out rigorous case-study research. My findings show how, by using the robustness framework and different collapse theories together, we can analyze the robustness or fragility of a CIS to specific shocks, in this case to El Niño events. As I explain in the analysis in section IV, it seems that the Piura basin is very fragile based on almost all of the predictions of collapse theories, but the biggest strength is its growing stock of social capital. In small steps, user associations have been collectively working towards solutions for water conservation and public-infrastructure maintenance. There is a long way to go yet to be entirely robust, but with the right policies to encourage the strengthening of these associations, the Piura basin could become more robust to future El Niño events.

Method

As mentioned before, key variables and their relationship for developing CIS robustness theory are still being explored. Case-study methods seek to study phenomena in depth and in their context, and it is thus a very appropriate tool for early phases in the development of theories (Yin, 1994; Eisenhardt, 1989). Case studies describe a social construction of reality (Searle, 1995), which can be sensitive to subjectivity, but if properly managed, can enable the researcher to better understand participants' views of reality, and their decisions and actions (Crabtree & Miller, 1999).

For internal validity, and to facilitate logical reasoning that is powerful and compelling enough to defend a research conclusion, Yin (1994) and Miles & Huberman (1994) recommend the use of a clear research framework. The Robustness Framework (Anderies et al., 2004) was created to systematically develop a theory of CIS robustness. This framework, which was later adapted by Anderies to apply to system relationships among the different types of infrastructure, social, human, natural, hard, soft, private, and public (Anderies, 2016), helps to identify key components (infrastructures) and the relationships among them, and to foresee potential perturbations and the system outcomes they might produce.

I used the Robustness Framework in this research to explore how the variables that it proposes might be connected to produce robust or not responses in the Piura Basin CIS when confronted with El Niño events in 1982/1983 and 1997/1998. For building validity, I follow the analysis of propositions as recommended by Yin (2003) and Miles & Huberman (1994) that comes from theories or hypotheses proposed in previous research of robustness, collapse, and disaster management. Figure 4.1 shows how the proposition and the robustness framework were used together to guide data collection and data analysis.



N	Proposition (causes of fragilities)	Reference	Framework
[1]	The system is too complex and rigid	Tainter (1988)	D and Link 3
[2]	Overshoot (large number of users with respect to the resource system)	Culbert (1973, 1988); Redman (2004, 2005); Holling (2001)	A, B and link 9
[3]	Physical constraints to adapt to new circumstances	Diamond (2005)	A, D, E and link 4
[4]	Selfish elites	Diamond (2005)	C
[5]	Centralized governance in a main productive resource	Lucero (2002)	Link 4
[6]	The fragility is transmitted by the interconnection of systems	Brunk (2002)	Link 7 and 8
[7]	Attachments to values that are detrimental to the environment	Diamond (2005)	B and C
[8]	High definition of "subsistence"	Pezzey and Anderies (2003)	B and link 1
[9]	Class conflicts	Gray 2008, Woods 2009	B, C and link 2
[10]	Poor anticipation capacity	Diamond (2005)	D

Figure 4.1: Robustness framework and propositions for the analysis.

I used secondary (journal articles, situation reports, newspaper columns, internet articles) and primary data, as recommended by Patton (1990) and Yin (2003), to supplement and compensate for the limitations of each other. I collected primary data from fieldwork in Lima (for national governance information) and Piura during the month of July, 2016. I performed semi-structured interviews (protocol shown in Appendix E for transparency and replicability). Different kinds of actors were interviewed: five farmers, three members of the Local Water Authority (ALA), two members of the National Water Authority (ANA), the Vice-minister of Environmental Disasters Prevention (Ministry of Agriculture), three members of academia, four major infrastructure managers, two minor infrastructure managers, and one archeological expert on the Mochica civilization that flourished in the Piura Basin from about [100–300 to 500–800 AD] and was erased from the map after a series of El Niño events. Secondary data provided the guidelines for primary data gathering and for cross-validation in an iterative fashion. Finally, I created a database (see Appendix F for the summarized database) to organize collected data as suggested by Yin (2003) and Stake (1995), and which shows the results prior to analysis. I present in the following section a summary of the results; however, a much more detailed results description of results and how they connect to the robustness framework is presented in Appendix F.

Case Study: El Niño in the Lower and Middle Piura Basin

El Niño. El Niño is a climatic phenomenon related to the warming of the east equatorial Pacific Ocean, which happens cyclically but erratically. The cycle takes between three and eight years, but with the impacts of climate change, we expect it to be more frequent (Bustamante, 2010). El Niño is the warm phase of the three phases of the El Niño Southern Oscillation (ENSO). The cold phase is called La Niña, and the third phase is the “normal” phase from which El Niño and La Niña deviate (Andrus et al., 2008). El Niño, in its most intense manifestation, causes catastrophic floods in the equatorial zone, and especially affects the southern coast of Ecuador and northern coast of Peru. El Niño is rated from “moderate” to “very strong,” depending on the sea-temperature change and its intensity. When El Niño is moderate, it can bring more benefits than damage as, for example, the regeneration of dry forests, and even the creation of new water sources (Woodman, 1998; Brack & Mendiola, 2000). In the 20th century, the two El Niño events rated as very strong were those of 1982-1983 and 1997-1998, the latter being the strongest episode ever recorded. During the El Niño of 1997-1998, the precipitation in Piura was 260 times the average of normal years. The excess precipitation flooded the city and surrounding agricultural fields, destroyed crops, irrigation infrastructure, and roads, and took dozens of lives (CAF, 2000).

There is evidence that the Peruvian north coast has been affected by El Niño for centuries, and that even an ancient civilization that was located in the north coast of Peru, including the Piura basin, the Mochica, collapsed after a very strong El Niño event (Fagan, 2010). The effects of El Niño have been recorded and analyzed as discrete incidents in windows of time and economic sector. They have not been analyzed longitudinally or using a systems-thinking approach, as I propose to do in my analysis. The Piura Basin is threatened with more frequent and more intense episodes of El Niño than the episodes that Piura has experience so far, which makes an urgent case for studying past vulnerability and robustness in order to direct current policies and to avoid potential catastrophic events.

The Lower and Middle Piura Basin ("Medio y Bajo Piura"): A Picture of the Current CIS. The Piura River is 280 kilometers long, and the basin surface is 12,216 km^2 (see Figure 4.2). The basin is divided into two irrigation systems, "Alto Piura" on its right margin in the highlands, and "Medio y Bajo Piura" on its left margin on the coast. I focus my analysis on the Medio y Bajo Piura sub-basin, because this area is more exposed to El Niño flood events than the Alto Piura sub-basin. Water from the Piura River is almost completely used before reaching Medio y Bajo Piura, but the sub-basin receives water from the Poechos Dam (on the Chira River) through the "Daniel Escobar" canal that was built in the 1970s (GRP, ANA & GTZ; 2009).

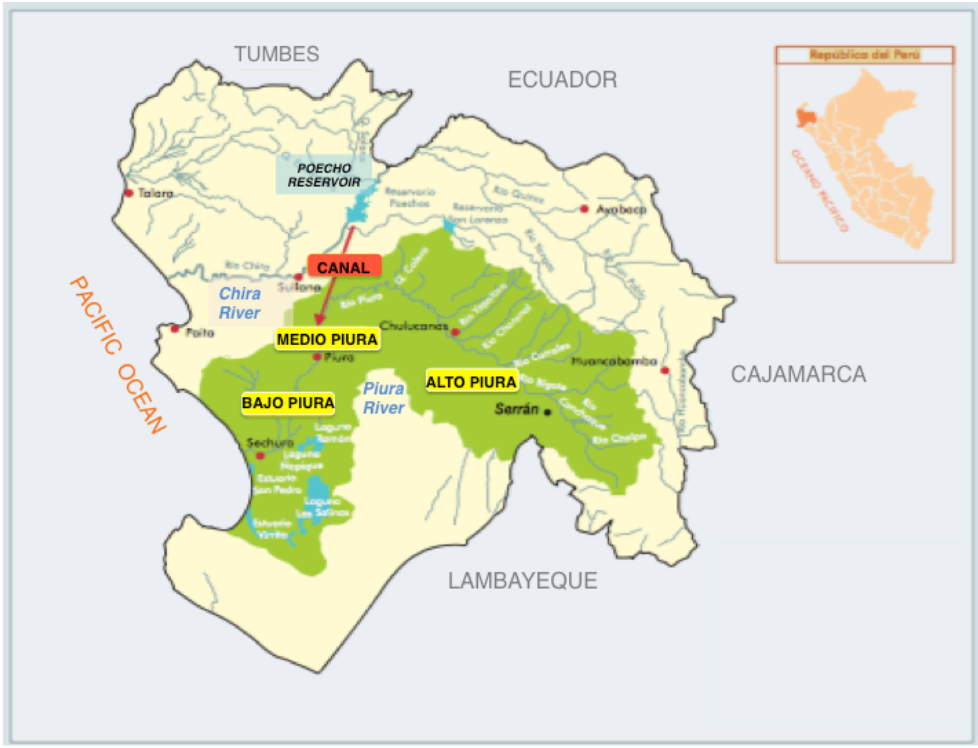


Figure 4.2. Map of the Piura Basin.

The Piura River's flow is normally low, but in El Niño events the river grows to a point that it becomes dangerous. For example, in the station of the river that is called "Sanchez Cerro," river flow in a normal year is no more than $140m^3/s$ at its highest, but in 1983 it increased to $3,200m^3/s$, and in 1998 to almost $4,500m^3/s$, damaging irrigation and road infrastructure (GRP et al., 2009).

Agriculture is an important activity in the basin, involving about one-third of the population (INEI, 2012). 48,534 ha are used for agriculture, of which 84% is irrigated. There are 75,176 farmers with small parcels averaging 0.65 ha. By 2016, the main crops in the Medio y Bajo sub-basin were rice (67%), corn (23%), and cotton (7%), all of which have a safe market, with their growers having access to credit and technical assistance. There is a small but growing group of farmers who are starting to grow mango, peppers, grapes, and other fruits (GRP et al., 2009).

To be eligible for irrigation, farmers must be members of the non-governmental and non-profit National Irrigation Association, *Junta Nacional de Usuarios de los Distritos de Riego del Perú* (JNUDRP), which is subdivided by valleys, and to be registered in the Local Water Authority of the Region (ALA). For the Lower and Middle Piura, there are three irrigation associations: Lower and Middle Piura, Sechura, and Huancabamba. Farmers elect association leaders, and although the participation in elections is low (less than 50% of attendance), farmers feel that they are well represented. This may be a result of a well-articulated network of sub-associations. The three main associations are divided into users' commissions, which are subdivided into canal committees, which at the same time have 10 delegates that are elected by and represent 200 farmers. The main role of the association is to operate and maintain the minor public irrigation infrastructure (secondary canals and drainage systems), distribute water, collect and manage fees for water use, determine water tariffs, cut water services to non-compliant farmers, represent water users in meetings with other associations and governmental authorities (e.g., National Water National Authority, Regional Government of Piura, Agriculture and Environmental Ministries, and major infrastructure operators called "Proyecto Especial Chira Piura"), and to generate activities for the economic, social, and institutional development of agriculture in the area (Gallo & Oft, 2011).

The Piura basin still has high poverty rates[19] (80%), which combine with poor territorial planning, negative impacts from mining activities, deficient road networks, and climate hazards to create a vicious circle and high obstacles to development (GRP, 2007). This situations persists in spite of all the efforts from governmental, non-governmental, and international organizations that have together worked for years on developing environmental and social management plans, capacity building, and implementation of sensitization programs due to their awareness of the vulnerability of the region, given the current ecological and social conditions, to climate change (see Appendix F).

The Piura Basin presents attractive features for agriculture and trade: good weather conditions with different ecological zones that allow for a diversity of crops, forest on the highlands of the basin, sea life on the ocean, significant rivers running from the Andes to the Pacific Ocean, and a central geographic location that is excellent for trade in the region. However, at the same time, the basin presents a fragile ecosystem with major challenges for human settlement. This is not only due to cycles of droughts and floods from El Niño. It is also because the basin's proximity to the ocean makes the land subject to salt intrusion; its flat slope in the lower basin makes the land prone to salinization and vulnerable to floods; its proximity to very steep mountains in the east means that rivers run strong in flood events and create mud-slides; and, finally, the basin is prone to desertification because of it characteristics as an arid region with low precipitation.

[19] Poverty defined as the percentage of the population that has at least one unsatisfied basic need. See table in Appendix F.

Ancient civilizations in the Piura Basin: Learning from the past. The Piura Basin has attracted multiple settlements and supported societies dating from 9,000 B.C., according to available information (Huertas, 1996). The Mochica society (or Moches) is one of the most famous civilizations that settled in the Piura Basin for approximately 700 years, (from around 100–300 AD to around 500–800 AD). The Moches were agriculturally based, with a well-developed and large network of irrigation canals and reservoirs (around 816 km) to divert and store river water to supply their crops in desert areas. Archeologists (Larco, Uhle & Kroeber, 1945; Butters & Castillo, 2008) think that the reason why the Moche society was much wealthier than other societies of the same period was their irrigation capacity. Their main agricultural products were corn, peanuts, cotton, fruits, and, in the highland areas, different types of potatoes (Velásquez, 2015), which they traded with other societies (Butters & Castillo, 2008), especially in the highlands to the east.

The society collapsed after being affected by El Niño, but that climatic disaster was not the sole cause of collapse. Obviously, the Moche would have experienced hundreds of El Niño events over their history. Thus, other factors must have been involved that led to the end of Moche civilization (Diamond 2005; Butters & Castillo, 2008). There are different hypotheses about the factors that could have contributed to the collapse. One relates to the centralized and very hierarchical political system, with a caste of religious and military leaders dominating farmers (Bouden, 1996). Societies that have a centralized governance structure over a main resource for the community, as is the case for many irrigation systems, tend to become trapped in a downward spiral of social crisis when rulers lose control of the main resource as a consequence of climatic changes. The crisis starts with the collapse of power of rulers as they lose credibility and their capacity to collect tribute, which at the same time potentiates the disruption of the hard (e.g., the reservoir) and soft (e.g., rule enforcement) public infrastructures, which in one way or another ends up decreasing the population's wealth. The decrease in wealth causes internal conflicts, population migration, or population loss due to decreasing health. The Maya civilization is a well-studied example that is similar to the Moches in this sense (Lucero, 2002).

The collapse of the Moche civilization resulted in the death of many of its citizens. Those who survived migrated to the highlands, where they later merged with other civilizations. It seems that after the collapse of the Moches, the communities that arose were well aware of the risks of settling in the coastal area of the Valley, and for centuries the population remained in the higher areas of the basin. Another hypothesis is that they maintained their location in the highlands because of its proximity with the most developed civilization of the time, the Inca Empire, which was mainly established in the highlands of the region.

The beginning of the current CIS in the Piura Basin. When Spanish conquerors arrived in South America, in 1532 A.D. they founded the first Spanish city in what is now the Peruvian territory of Piura (San Miguel of Tangaraná). When the leading conqueror, Francisco Pizarro, and his army arrived in Piura, they found an organized society settled only in the Andes (Huertas, 1996). Some speculate that this was one of the reasons why the Spanish decided to found a city in Piura, but also because of its proximity to the biggest port of the Americas (Paita), combined with the presence of the Chira and Piura Rivers which they probably imagined would make agriculture possible (Bonilla &

Hünefeldt, 1986). The Spanish were not aware of the ecological dangers of the lower region of the Piura Basin, nor were the later independent Peruvians, who developed a bigger city in the Valley by 1821.

Agriculture in the area changed after the arrival of the Spanish conquerors. It was monopolized by a few owners who possessed large pieces of land (*haciendas*), and cultivated only a few types of crops (monocropping, especially of sugar cane and cotton), following market incentives. In the 1970s, to increase the region's capacity to cope with drought seasons, the government planned and built the biggest reservoir in Latin America: Poechos Reservoir. The Peruvian president by then was General Velasco, who is remembered mainly for being the last president to date to take power after a *coups d'état,* and for being the author of the Agrarian Reform of the 1970s. The Agrarian Reform aimed to return the agricultural land owned by *hacendados* to the people who had worked it for decades and who, during the reform, were organized in cooperatives. To strengthen the reform process, the first water law[20] was formulated, initiating a series of water policies that, in one way or another, place agricultural activity at the center of the articulation of water law. It was in this context that the Poecho Reservoir and its related infrastructure were built. With the execution of the project, water from the Chira River (which flowed through land with less agricultural potential that the land in the Piura Basin) was diverted to the reservoir, and then released into the Piura River, favoring farmers of the Lower and Middle Piura.

Thanks to this project, water availability became stable, and agricultural activity started to grow. In only 10 years, agricultural land area grew by 10% (from 84 000ha in

[20] Decreto Ley Nº 17752 of July 24th of 1969 (a month later of the promulgation of the agrarian reform law)

1976 to 93 000ha in 1986), and population grew as well (3% per year in the same period, as shown in Appendix F). Now, Piura produces 7% of all agricultural output in Peru (INEI, 2016), and is the second most-populated region of the country[21]. However, even though currently the Lower and Middle Piura is robust to droughts, the other effect of El Niño phenomena, floods, is still a problem. In 1997/1998, flood episodes affected 120,637 people in Piura, destroyed 10,255 houses, took around 200 lives, and were responsible for 40 million USD of crop loss (Indeci, 1999).

Robustness – Fragility Analysis of the Lower and Middle Piura sub-Basin to flood events

The Moche society was well known for its engineered irrigation system, with big reservoirs and long canals. But even with this human-made hard infrastructure, the Moches were unable to cope with the severe droughts and floods from El Niño events. In the end, the remaining population decided to migrate to the high areas of the basin. After many decades of the collapse of the Moches, in the 1970s, policymakers unaware of the dangers of El Niño, attracted and incentivized population growth in a region highly exposed to strong floods, by building hard public infrastructure (e.g., reservoir, canals, roads, bridges) and soft public infrastructure (e.g., water law, agrarian reform). According to Tainter's (1988) theory of collapse, this complexity puts at risk the robustness of the system, and it is now more difficult to mobilize a big population to relocate to another region less exposed to environmental perturbations.

[21] Note that the Piura capital, also called Piura, is located in the lower basin of the Piura River.

In this sense, a *"path dependence"*[22] of community development with economic incentives has already been built in the lower region of the Piura Basin, anchoring the settled society to the basin. This is of special importance because the poverty level is still high, with many basic needs unfulfilled for a big part of the population, and the population has low education levels (see Appendix F). This population has limited options for migrating.

Another theory of collapse that is related to the size of the population is the overshoot theory (see Table 4.1). As mentioned before, Piura is ranked second among regions of Peru in terms of population size (6% of total population), and the total amount of water available in this region is less than 1% of the total available in the country (CERPRAR, 2016). This is a common problem along the whole Peruvian coast, where more than 60% of the population share 2.2% of the available water (Crovetto, 2013). There are clearly resource-distribution issues in Peru that need to be addressed. This is not a problem that directly relates to the robustness of the system to flood events, but if the population continues to grow and water becomes scarcer, it will eventually become a related problem because it is linked to the wealth of the population. Traditionally, governmental policies have favored the coast more than the highlands and the Amazon; combined with the harsh topography of these last two regions, the government's lack of investment has left behind the highlands and the Amazon. Perhaps, a path to avoid the overshooting effect on the coast may be to create incentives for people to migrate from the coast to the other two regions, since according to Laguna (2011), the main migratory flows are to metropolitan areas and their relatively abundant economic opportunities.

[22] I use here the term "path dependence" as the phenomenon in which a set of decisions are constrained by earlier decisions, even though the circumstances in which they were taken are not relevant anymore (Westley et al., 2011).

Which infrastructures need to be enhanced or modified to increase the robustness of the Piura Basin's CIS system to floods? The most recurrent answer to this question has been the hard human-made infrastructure, namely canals, the reservoir, the drainage system, or even a modification of the river's capacity to contain water runoff. There are many projects that make this answer more specific, but the results are always the same: investment is insufficient. The Poecho Reservoir now has only 50% of its initial capacity (885 mmc), major canals are being maintained but not as much as needed (water distribution loss is around 15%), and drainage-system maintenance is almost completely ignored, leaving a significant part of the Valley with salinization problems (CERPRAR, 2016).

In this sense, the assessment of the Piura Basin with respect to theory 3 from Table 4.1, "Physical Constraints to Adapt to New Circumstances," reveals a degree of fragility. If we dig into the potential causes of this fragility, using the robustness framework, we then shift our attention to what affects the public infrastructure: public-infrastructure providers. The costs of public infrastructure to prevent the negative effects of El Niño costs are borne by the regional government, the central government, international aid, and water user associations.

Of all the public-infrastructure providers, it is the regional government that has the main responsibility of allocating part of its budget for disaster prevention on an annual basis. My interviewees mentioned that the regional government is more concerned about re-election and public visibility than in the effects of El Niño, which are not a constant concern, it prefers to invest in parks or other types of infrastructure that can be appreciated in the short term by the population. However, after an unexpected Niño in the beginning of 2017, in the media we could see how an angry population was complaining about how little the government had spent in prevention programs[23]. When we assess this aspect of the CIS with respect to collapse theories, this fragility is revealed by the theory of "Selfish elites" listed as number 4 in Table 4.1

But there are other aspects of regional governance performance to explore. Peru had centralized the nation's governance until 1990. Then in 1988 with the "Law of Basis for Decentralization", the central government transferred responsibilities and resources to the by then recently-created regional governments for the enforcement of their regional governance rights. This transfer was abrupt and was not accompanied with adequate local capacity-building for the new governance regime to handle responsibilities and meet challenges (La Contraloria, 2014). There are no indicators for assessing the performance of the decentralization process, but even though there is an awareness that resources are limiting factors for economic growth and development in Peru, the regional governments do not spend their allotted budget entirely. For the 2005-2012 period, they executed less than 60% (La Contraloria, 2014), and although expenditures have been increasing progressively to 78 % in 2014 and to 81% in 2015, the underuse of financial resources has created a tension among the central government, the regional governments, and the population (GRP, 2016).

Further, it seems that the central government, rather than investing in regional-government capacity building, is reducing the regional budget. Between 2013 and 2016, the percentage of the initial yearly budget for the national executive branch has increased from 63% to 75%, leaving proportionally less to the regional and local governments

[23] See March 25th 2017 peru21 newspaper as an example, url: https://peru21.pe/lima/peru-funciona-prevencion-desastres-infografia-70325

(GRP, 2016). This indicates that a phenomenon termed recentralization[24] is occurring (GRP, 2016). Recentralization is another threat that is highlighted by the collapse theory listed as number 5 in Table 4.1: "Centralized Governance," and is one of the suspected causes of the Moche collapse.

It is not only that regional governments' share of Peru's national budget is decreasing, but also that the national government bureaucracy limits the planned expenditures of regional agencies. Moreover, the fit between sectorial policies that come from the executive branch and the regional conditions in which the local governments operate is poor (La Contraloria, 2014). None of the collapse theories suggest failures in polycentric governance as a potential cause of CIS collapse, though the empirical evidence of this study suggests the critical importance of a good working relationship between different centers of decision-making.

The interconnection theory (number 6 in Table 4.1) is relevant to El Niño's effect on many regions at the same time. In Peru, the impact is even more notable than elsewhere because El Niño affects almost the entire country. The degree of help that any one system can receive depends on the impact that other regions experience concurrently. International programs have played an important role in recovery after El Niño events, and even for post-disaster prevention programs (e.g., USAID, UE, GIZ). Governmental aid has played an important role also but it has not been forthcoming as quickly as it could have been. By 1983, Peru had a centralized government, and in 1997 the decentralization process was still weak. This limited reaction strategies, especially

[24] Recentralization is defined as the non-officially manifested action of the central government where the decentralization process is reverted, manifested by the return of some of the resources allocated to regional governments to the central government (Cook, 1990).

because the disaster was happening simultaneously in different regions of the country. After the El Niño of 1983, with the help of the international community, Peru was able to monitor and predict future El Niño events. For the El Niño that started in 1997, it was possible to know six months in advance that threatening floods were likely to happen. The government, led by President Alberto Fujimori, undertook a massive damage-prevention campaign, but it was not enough to prevent disastrous events. In Piura, the government proposed to construct a drain to reduce the volume of water in the Piura River by diverting it to the ocean, but because of limited resources, the plan never materialized. As a result, 374 people lost their lives, another 412 were injured, and close to 600,000 were affected by the disaster (PREDESS, 1998).

Table 4.1Robustness Fragility Assessment According to Collapse Theories

N	**Proposition (Causes of fragilities)**	**Robustness – Fragility Assessment**
[1]	The system's complexity and rigidity	**Medium** Because of government policies for agricultural development (including the construction of a big reservoir), among other reasons, population has grown at a fast pace for the past decades in the Lower and Middle Sub-basin. Population migration to safer regions is unlikely.
[2]	Overshoot (large number of users with respect to the resource system)	**Fragile** Piura is the second biggest region of the country and has limited water available. Agricultural expansion is one of the causes of deforestation and land degradation upstream of the Piura River, where the runoff during flood events increases.
[3]	Physical constraints on adapting to new circumstances	**Fragile** The Poechos Reservoir helps to capture water from floods. It has, however, lost its 50% of capacity. The Poecho project (canals, reservoir, and drainage system) has a high cost of maintenance due to its size, and its water-retention performance in flood events is low. The Lower and Middle Sub-basin is located in an area of flat slope, right next to regions with steep slopes. This makes the river runoff in flood times dangerous.

[4]	Selfish elites	**Fragile** Corruption is still a problem in Peru.
[5]	Centralized governance in a main productive resource	**Fragile** The decentralization of power has not worked as expected. Central government has to make decisions for investment in disasters prevention for many regions of the country at the same time.
[6]	Systems interconnection	**Fragile** El Niño is a global phenomenon that impacts Peru in different regions at the same time. The causes and consequences that are strongly connected for making the event a disaster are place based in different regions.
[7]	Attachments to values that are detrimental to the environment	**Robust** After sensitivity programs, the awareness in Piura of the environmental threats in the Basin has increased. This has encouraged users in Lower and Middle Piura to be more involved in promoting collective action in water management and disaster prevention
[8]	Subsistence	**Fragile** High poverty levels. Population in poverty conditions is fragile to environmental disturbances because of their dependence and relationship with resources.
[9]	Class conflicts	**Medium** There are some disparities, but there are no problems related to inequity.
[10]	Poor anticipation capacity	**Fragile** There is awareness of climate change and how it will affect the intensity and frequency of El Niño events. But it is still difficult to anticipate well in advance when a Niño will occur. The 1997/1998 event was anticipated 6 months in advance, but the 2017 event was not noticed in advance.

The last relevant group of public-infrastructure providers is the water-users association. Fortunately, the institutionalization of the water-users association of the Lower and Middle Piura shows encouraging results. Farmers seem to understand the importance of improving water management and the role of the water fee in its success. The multi-level organization that they have crafted, from delegates of each 200 farmers, to a sub-basin water association of 75,176 members, is time efficient, enables fluent coordination, effective monitoring, and increases efficiency in communicating concerns or claims and even in solving conflicts in different instances. The water associations still have to reduce the default rate of water-fee payments, and to agree on a higher price that reflects the real cost (public and social) of water. However, they have made an improvement from 2014 to 2015: fees collected increased from S/4 million (around USD 1.2 million) to S/6 million (around USD 1.8 millions). Different actors that have responsaiblities as managers (e.g., National Local Water Authority, Mayor Operation Managers), revealed their satisfaction with the progress that the Lower and Middle Piura Water Users Association has achieved. They have improved by themselves the minor canals that they are in charge of maintaining and have collected their own funds for emergency events. As we can see in Table 4.1, the assessment with respect to the theory listed as number 7 "Attachments to values that are detrimental to the environment" indicates a degree of robustness to flood in the basin, given that farmers' behaviors are showing more engagement in contributing to the public infrastructure provisioning.

However, farmers' technical knowledge in the basin is limited, and farmers' agricultural practices and water management capabilities are still developing (CERPRAR, 2016) which makes their individual economic development slow. Poverty conditions are also linked to environmental degradation. Poor farming practices (e.g. excessive watering, pesticide and fertilizer use, no crop rotation) degrade the soil and, at the same time, lock farmers into low economic returns on land and labor. Farmers with low profits cannot contribute enough to maintain irrigation infrastructure, especially because of the size of the population (high transaction costs), and because of the large scale of the infrastructure (high maintenance costs). Moreover, Lower and Middle Piura share the irrigation infrastructure of the Poecho Project, including the reservoir (see

Figure 4.2), with the Chira Basin. This fact makes the transaction cost of coordinating to collect enough resources for infrastructure maintenance even higher, especially because the Chira Basin has less-developed collective action than Lower and Middle Piura.

The government has now unofficially announced that it will progressively reduce its financial assistance for major infrastructure maintenance. User associations will therefore need to grow even stronger to ensure public provisioning, in this case through water tariffs. Moreover, self-financed systems are becoming more and more necessary because of the reduction in support from international aid sources. Since Peru has improved its human development in literacy and GDP per capita, it is now a country that is less prioritized for international aid (GRP, 2016)

One of the explanations that farmers in the Lower and Middle sub-basin give for avoiding water fees is that they have low returns on their water use for farming. It may be, then, that investment in soft infrastructure (e.g., capacity building for farming practices) should be a priority, or at least as important as hard-infrastructure investment. One current project aims to build a reservoir for Upper Piura, but has not yet solved the problem of funding for resource maintenance. Farmers and managers could learn from past experience with Lower and Middle Piura, and plan for investment in soft infrastructure at the same time. Another option for governance improvement is to encourage labor work on public infrastructure in lieu of water fees, given the high poverty rates.

When farmers ensure that their efforts are not in vain and that they actually fulfill a need, they are more likely to participate in collective action (Wade, 1988). In this sense, the high level of corruption is a problem ("selfish elites" theory listed as number 4 in

Table 4.1). If regional and national authorities do not convince farmers'–and water users in general–that their own efforts in provisioning (or paying tariffs, taxes, etc.) have a high expected return in terms of improving their welfare, their incentive for collective action will decrease, as described in Chapter 3. El Niño events revealed hard and soft infrastructure weakness: poor emergency response, recently built bridges that were destroyed, and projects on hold because of bureaucracy, for example. These are discouraging feedbacks for the population, but they may strengthen the argument for promoting local, self-organizing, problem-solving associations. In this sense, governance transparency or users' project involvement may be some valid options.

It seems that everyone in Piura is well aware of the importance of increasing the capacity to prevent damage from El Niño events. However, most of the time the policy focus is on hard infrastructure and less on improvement of governance infrastructure. Information about hard infrastructure, e.g., reservoirs, canal maintenance, dams, and drainages, is available and well understood, but the source of funding for hard infrastructure maintenance is barely considered (generally it is assumed that it should come from the central government). From the analysis summarized in Table 4.1, we can see that the most robust aspect of the system is the way both individual, and networks of, users' associations are developed. It is, however, still far from being ideal, and the analysis shows that it can make a significant difference if the associations get support to build their capacity and to become more knowledgeable about how authorities can support them, how to get out of poverty traps, how to better manage their resources, and how to prepare better for future threatening events. Since poverty and developing agricultural practices are aspects that are identified as root causes that show fragilities in the system, by underpinning this strength there might be a positive effect on other aspects of the system.

Concluding Thoughts

By reviewing the Lower and Middle Piura sub-basin while addressing a research question that presumes causal links from a set of conditions drawn from past research on collapse theories along with variables and links in the Robustness Framework, it was possible to assess the aspects of which a CIS is robust or fragile to a disturbance, in this case El Niño events. It seems that, in general, the CIS of the Lower and Middle Piura sub-basin is fragile to future drought and flooding events but has demonstrated a solid strength, significant capacity for collective action, which is an important social infrastructure to build on to prevent damage from future Niños and to develop sustainably.

As shown in this study, public infrastructure is an essential feature of functioning societies within CIS, and for CIS robustness. However, too much attention has been paid to physical infrastructure, with the result that opportunities to strengthen CIS have been overlooked. If we pay more attention to the soft public infrastructure, we may find some more effective potential solutions for increasing the robustness of the system to floods. In addition to strengthening water-users association as discussed earlier, attention to how to improve the coordination among different levels of governance seems to be necessary.

This is the story of the Piura basin CIS. There are many other similar cases in Peru, and around the world, that will be exposed to future climate change events. Because this was only one case study, I cannot draw any general theoretical conclusions. However, this research provides methodological and theoretical insights that can contribute to theory building for robust CIS, which is an urgent endeavor. Future research can use the same methodological approach to analyze more cases and refine the theory.

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CHAPTER 5

TOOLS FOR DESIGNING ROBUST SYSTEMS TO ENVIRONMENTAL SHOCKS: THE NORTH PERUVIAN COAST CASE

Introduction

An important characteristic of Coupled Infrastructure Systems (CIS) - such as irrigation systems, forests and fisheries – is that they are constantly changing (Berkes & Folke 1998, Scheffer et al. 2009). The dynamic of CIS is created by the interaction among the different types of infrastructures that constitute the system itself: users (social and human infrastructure), watershed (natural infrastructure), reservoirs, (human-made hard infrastructure), and institutions (human-made soft infrastructure) (Anderies, 2015). This dynamic can be temporarily or permanently affected by internal or external disturbances that impact one or more infrastructures (e.g., population growth that affects social infrastructure, droughts that affect natural infrastructure). Thus, the sustainability of a system depends on both the dynamics among its infrastructures and on how those dynamics influence the system's capacity to cope with potential catastrophic shocks (Schlüter, Hinkel, Bots & Arlinghaus; 2014, Carpenter et al., 2009).

Because time-series data on CIS are scarce and experiments on CIS are difficult to perform, dynamic modeling and longitudinal case studies are perhaps the most feasible methods for understanding CIS dynamics (Carpenter & Brock 2004), and they can be used to complement one another (Janssen & Anderies, 2013). Dynamic models are simplified formal representations of the structure and processes of real-world cases. They incorporate those theoretically or empirically identified components, and the relationships among them, that are relevant to answering a specific question about the behavior of a system over time (Schlüter et al., 2014). Dynamic models are also useful for exploring robustness theory because they make it possible to analyze system feedbacks under potential disturbances (Janssen & Anderies 2013). When they are empirically tested, they can be useful tools for CIS management (Baumgärtner et al., 2008).

A dynamic model was developed to answer the research question, "What interventions can policymakers implement to make CIS robust to the shocks expected from climate change?" Because the answer to this question is complex and context specific (Ostrom, Janssen & Anderies; 2007), I partly address this question by studying an irrigation system from the northern Peruvian coast: the *Bajo y Medio Piura* sub-basin. The north coast is now threated by disastrous flood events followed by acute droughts caused by climate change, but it has also been affected by these extreme events in past centuries. The effect of past environmental shocks in this region is analyzed in Chapter 4, and the results of the analysis has contributed to the design and testing of the dynamic model.

Extreme flood events damage human-made hard infrastructure through which, for example, farmers are able to appropriate water to irrigate their crops (Anderies, 2015). In arid regions like the north coast of Peru, the characteristics of the public, human-made hard infrastructure are critically important because agricultural activity depends entirely on that infrastructure. Dams and reservoirs capture runoff from the mountains, smoothing flow variations and saving surplus water for later use (Ostrom et al., 1994). It is crucial to understand the interactions between hard infrastructure and the other components of an irrigation system because water is distributed through a river or canal network which, in turn, creates asymmetries that affect the structure of the social dilemmas in irrigation systems (Ostrom et al., 1994). Hard infrastructure is also affected by how it is maintained (that is, by how much users collectively invest in it; see Figure 1), and maintenance is affected by how appropriation and provisioning dilemmas are solved.[25] In commons dilemmas there is always the temptation of non-compliance, so how users monitor and sanction non-compliance is a key component that affects system outcomes (Ostrom, 1990). This is especially relevant when, as on Peru's north coast, users are settled along a canal or river, which decreases the visibility of their actions.

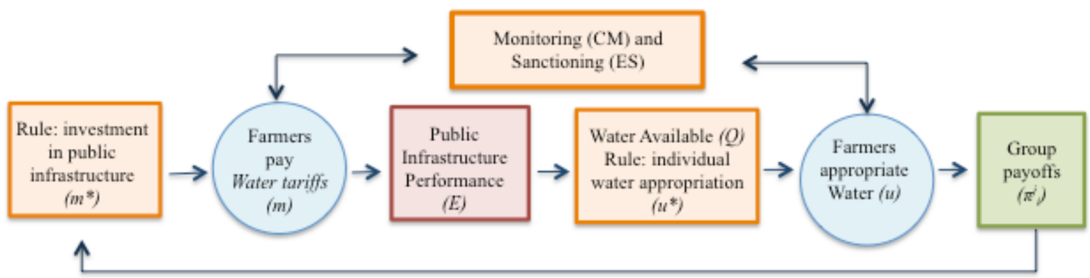


Figure 5.1.A Feedback Control Loop of the Characterized Irrigation System

The research problem to be addressed in this chapter has two parts:

- *To understand the core dynamics of the systems* I ask: How does public-infrastructure (hard and soft) performance affect collective action in

[25] The provisioning dilemma is created by the incentive of increasing one's own net benefits in the short term by not contributing to public infrastructure provisioning, because the user will benefit from the provisioning anyway. The appropriation dilemma happens because farmers are temped to use more water than allowed to increase their profits, but by doing so they will prevent other farmers from increasing their own profits because there is not enough water available for all users to maximize their profits (Dietz et al. 2003). The two dilemmas are interrelated since the public infrastructure is necessary to appropriate water, and a user's decision to invest in the public infrastructure depends on their perceived benefits from appropriating water.

the asymmetric irrigation systems of the Peruvian north coast? Hard infrastructure is represented by reservoirs, dams, and canals; and soft infrastructure by monitoring and sanctioning.

- *To analyze how the systems respond to environmental shocks* I ask:
    - How robust are irrigation systems on the Peruvian north coast to natural, extreme flood events?
    - What interventions can increase the robustness of these systems to extreme flood events?

To address these questions I propose an evolutionary game theoretical model, as Yu et al. (2015) used in order to study the impact of infrastructure on collective action and system stability in irrigation systems. The replicator dynamics of the model is a modified version of the one proposed by Taylor & Jonker (1978). I represent the structure of the social dilemma based on the model developed by Rubinos (2013), and the effects of sanctioning and modeling in users payoffs on the proposed equations by Sethi and Somanathan (1996). I calibrated the model using evidence from the Peruvian irrigation system “Bajo y Medio Piura” that presents general characteristics and threats of the north Peruvian coast irrigation systems.

I used Matlab to simulate past events, users and biophysical reactions, and outcomes in order to verify model outputs for consistency with evidence in the sub-basin. The first part of the research problem was addressed with a sensitivity analysis that shows how the relationship of the human-made hard infrastructure (also called engineered infrastructure) with collective action is not always positive and thus, one-time investment in this type of infrastructure is not always effective. On the contrary, the model shows that by increasing enforcement mechanisms of sanctions to non-cooperative behavior can make a significant difference, specially if farmers perceive that it is likely that non-cooperator will be sanctioned for their behavior.

The second question is addressed with the analysis of *equilibria* in section 5.III. Constant investment in the maintenance of the engineered constructed infrastructure is needed, it seems that there is a threshold of investment that considerably increase the robustness of the system to floods. Additional strategies to increase the investment in the engineered infrastructure and thus the robustness of the system are later explored. The three strategies: increase of awareness (or change social norms), increase of water tariffs, and increase farming productivity, were simulated as effective, though some more than others. Finally, section 5.IV summarizes the results and analysis.

The Model: Evolutionary Game Theoretical Model

The Peruvian north coast is characterized by its low precipitation, and by its good sunlight conditions for agricultural productivity. Currently, 21% of Peruvian agriculture is produced in this region (INEI, 2015), but in order for cultivation to be viable, farmers have to capture and store water in a reservoir. In the model, I represent the water captured as "q," which depends on (1) naturally availability, "q^S," and (2) performance of the engineered construction (reservoir, canals and drainage system), "E." $q = Eq^S - \frac{(1-E)q^{S^2}}{\omega}$. "$E$" is bounded between 0 and 1, where 1 is the perfect performance that can never be achieved. The performance of the engineered construction captures the capacity to store and deliver available water, but also its capacity to contain water from rain through the reservoir, canals, rivers and drains. The quadratic shape captures the problem of flooding events divided by the parameter "ω" that indicates the threshold of precipitation to affect water availability. When the infrastructure is not well maintained or prepared for these events, water availability q is negatively affected.

To use and manage an irrigation system in Peru, farmers must create an association, which is supervised by the both the regional government and the national water authority (ANA). I assume that there are "N" farmers (a well–enforced, finite number affected by a boundary rule) who choose their leaders (managers). Irrigation association managers operate and maintain the public irrigation infrastructure (dam and canals), water distribution, collect and manage fees for water use, decide water tariffs, cut water services to non-compliant farmers, and represent water users at inter-institutional meetings (Gallo & Oft, 2011). For the purposes of the model, I assume that managers provide only the following public soft infrastructure (orange boxes of figure 5.1):

- Rules: Managers determine water tariff, "m^*," based on the comparison between the maximization of social welfare (explained below), the government support (explained below), and farmers ability to pay. Farmers have to pay this tariff before the allocation of water occurs. Based on Q, managers determine the maximum individual water withdrawal allowed: u^*

- The total contribution from water tariffs "m" (which is calculated by multiplying the number of cooperators "N^c" and the water tariff "m^*") is used to improve the performance of the engineered construction "E", which depends also on its past performance (E_{t-1}) because the infrastructure is not entirely rebuilt each year, and it is also affected by depreciation Θ. Also, because in the Medio y Bajo Piura sub-basin the engineered irrigation construction is very costly to maintain, the government plays an important role for its maintenance by contributing a fixed amount "ψ". The total investment for the engineered constructed maintenance and improvement is then; $v = m + \psi$, and affects the performance as described by the following expression:

$$E_{E_{(t-1),}m}\text{: If } v_{(m)} > 0, \;\; E_t = E_{t-1} + e^{\frac{-1}{(v)}} E_{t-1}(1 - E_{t-1}) - \Theta E_{t-1};$$

$$\text{If } v_{(m)} = 0, E_t = E_{(t-1)} - \Theta E_{(t-1)}$$

In strong flood events, the engineered construction can also be damaged, as happened in the El Nino events of 1982/1983 and 1997/1998. The effect of strong flood in the performance of the engineered construction will depend on how much the amount invested in the infrastructure performance offset the physical damage in the system. Then, in flood events, v can be expressed by the following equation:

$$v = m + \psi - \lambda(q^S - \omega)$$

where "λ" is the coefficient that express the effect on the engineered constructed performance of the excess of precipitation in the system. Normally, when the government knows that a Niño event is approaching, then their investment in prevention increases for that period (ψ). Then if the increase in ψ offsets the impacts of El Niño (expressed through $\lambda\ (q^s - \omega)$, then, the impact is reduced.

- Monitoring and sanctioning: Users in irrigation systems, as in other CIS, face the social dilemma of cooperating with the system by following the rules or not. Users base this decision on their payoffs, which can be pecuniary and otherwise, and which is explained later. Cooperators will assume a cost of monitoring (δ) to persuade users to cooperate and to impose a sanction (γ with a probability of enforcement (σ) to those who do not cooperate (N^{nc}). The expected cost of not cooperating is then $\sigma\gamma$, and farmers that do not cooperate assume this cost.

In most systems on the north coast of Peru, farmers withdraw water from a surface water source (river or canal), and users have access to the resource sequentially, generating an asymmetry among users where upstream users are clearly favored by having earlier access to water withdrawals than downstream users. To find out how this asymmetry plays a role in irrigation systems outcomes, I differentiate upstream users (N_1) and downstream users (N_2), with $N_1 + N_2 = N$. Upstream users have to decide how much water to appropriate of the total water available $q_{(v,q^s)}$, and downstream users (group 2) have a different amount of water available q_2^A, which will depend on q, and how much water is appropriated by all upstream users ($u_1 * N_1$), but also by the length of the canal "ζ" and its performance (which is also captured by E).

$$q_2^A = q - u_1 N_1 - \alpha q(1-E)\zeta$$

I assume that all users have the same information, same amount of land, grow the same crops, and have the same expertise in farming. These assumptions make the focused analysis possible because every farmer has the same production function, which depends on water units individually appropriated "u_i." When the production function $f(u_i)$ is multiplied by the price of the crop p, we have farmer's income, $I = p\,f(u_i)$. The costs of farming is assumed to be proportional to water use such that $C = \varsigma u_i$. For managers to find the optimal water tariff (m), they maximize the total payoffs of the system, assuming that all will cooperate:

$$\Pi = \left(I_{(m)} - C_{(m)}\right)N - m$$

$$\text{s.t } uN \leq q^A{}_{(\mathrm{m})}$$

However, the tariff imposed will depend on farmers' income. Farmers need to save some of their income for basic needs. Thus managers (that are also farmers) decide that the water tariff should not exceed a percentage "ζ" of their income. The payoff for a farmer will be also affected by the decision to cooperate (adding monitoring costs δ) or not (adding expected sanctions γP). Then the payoffs (π^j of the two groups of users are:

$$\pi^c = pf - cu^c - m^c - \delta$$

$$\pi^{nc} = pf - cu^{nc} - \gamma P$$

Note that cooperators pay the water tariff that managers impose, m^*, and appropriate water according to the rule u^*, where individual appropriation u_i^c is decided by maximizing cooperators' pecuniary payoff π^c with maximum amount of water they can appropriate u^*, such that $u_i^c \leq u^*$. Also, cooperators payment of the water tariff depends on their capacity to pay constrained by *I(u)*. Non-cooperators do not pay water tariffs ($m^{nc}=0$) and appropriate the amount of water that maximizes their pecuniary payoffs, π^{nc}. Both maximizations are also subject to $q_{(m,S)}$ and $q^1_{(m,u_1)}$ depending on whether the farmer is an upstream or a downstream user, respectively.

Table 5.1

Definitions of Variables and Relevant Parameters

Symbol	Definition
q	Produced water
$q_i{}^A$	Water available for group "*i*" *i*=1 upstream, *i*=2 downstream
q^S	Naturally produced water
E_t	Performance of the physical engineered construction in time *t*
N_i^j	Number of users j=c (cooperators), *j=nc* (non-cooperators) of the groups *i*=1 upstream, *i*=2 downstream.
S_i^C	Fraction of cooperators in group *i* *i*=1 upstream, *i*=2 downstream
m^*	Water tariff
m	Total water tariff collected by managers
u_i	Water appropriated *i*=group 1,2
u	Total water appropriated
u^*	Maximum water allocated to farmers that paid the water tariff
Π^C	Cooperators payoffs
Π^{NC}	Cooperators payoffs
$\bar{\Pi}$	Average payoffs of the system
Π	Total payoffs of the system
ρ	Relative speed of conversion from cooperator to non-cooperator
η	Parameter giving the monetary value of the additional output generated by the first unit of irrigation water
β	Parameter that determines how the marginal value changes as the amount of appropriated water changes
ς	Marginal cost of water appropriation
ζ	Length of the canal for group *i*
α	Coefficient of water loss
θ	Depreciation

Last, I assume that users are boundedly rational, and take a modified evolutionary approach to represent the decision-making process of farmers about cooperating or not. S_i is the fraction of cooperators, such that $S_i=N_i^c/N$, $i = \{1,2\}$, and $N^c{}_1 + N^c{}_2 = N^c$. In every period, which famers have to make a decision about cooperating, they compare the average income of all users $\bar{\pi}$ with their pecuniary payoff π^j *(j = {c, nc})*. If they end up losing in this comparison, they will consider switching to the other group (from cooperators *(j = c)* to non-cooperators *(j = nc)* and vice versa). Only some of the farmers will change strategy, as expressed in the following equation:

$$S_{it} = S_{it-1} + S_{it-1}[\max((\pi^c - \bar{\pi})/\bar{\pi}, 0) - \rho \max((\bar{\pi} - \pi^c)/\bar{\pi}, 0)]$$

This is a modified version of the replicator dynamics used by Taylor & Jonker (1978). I assume that the speed of conversion from non-cooperator to cooperator (β^{ncc} is different from the speed of conversion from cooperator to non-cooperator (β^{cnc}, and that $\rho = (\beta^{cnc}/\beta^{ncc})$. By differentiating between the speeds of conversion, I assume that users have more considerations than pecuniary payoffs alone (Van Lange, 1999), and that there might be a moral inertia that affects the decision to change from cooperation to non-cooperation. In this situation, $\beta^{cnc} < \beta^{ncc}$.

If the speeds of conversion are equal, then $\rho = 1$, then the replicator dynamics will be the same as those used by Taylor & Jonker (1978)[26]: $S_{it} = S_{it-1} + S_{it-1}(\pi^c - \bar{\pi})/\bar{\pi}$. As it can be seen, the traditional replicator dynamics is a subset of the proposed replicator for this research.

The equations for each function and the model summary are shown in Table 5.2, and an explanation diagram in Figure 5.1.B. The equations have been modified or

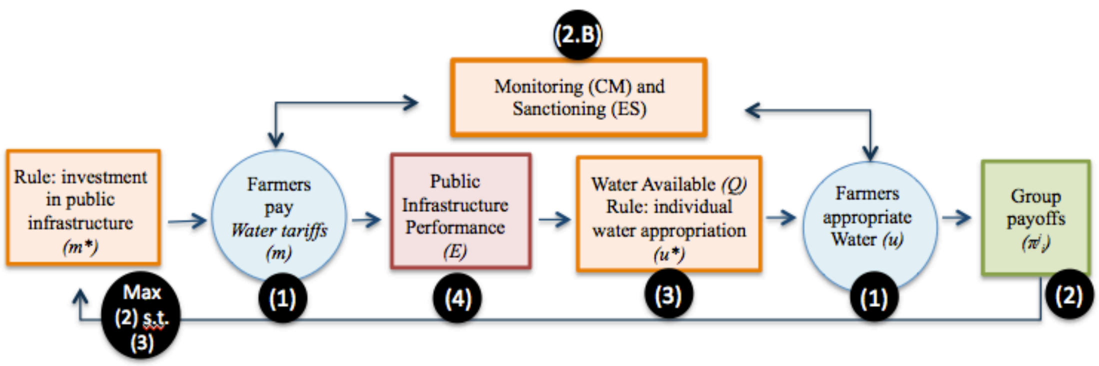
[26] Taylor & Jonker (1978) replicator dynamic was not specific to benefits but to strategies fitness of a strategy.

validated according to the findings about the interactions between the hard, human-made public infrastructure and water availability in the Medio y Bajo Piura sub-basin.

Table 5.2

Model Summary

Main Equations	Rationale
Modified Replicator Dynamic	



$q_2^A = q - u_1 N_1 - aq(1-E)(\zeta)$	(3.B) Downstream (i=2)
Engineered Performance	
If $v_{(m)} > 0,\ E_t = E_{t-1} + e^{\frac{-1}{(v)}} E_{t-1}(1-E_{t-1}) - \Theta E_{t-1}$	(4.A) Engineered Constructed performance as a function of its maintenance investment
If $v_{(m)} = 0, E_t = E_{(t-1)} - \Theta E_{(t-1)}$	(4.B) Same as 4.A when *v=0*
Production Function	
$F_{(u)} = \frac{\alpha}{p} u - \frac{\beta}{p} u^2$	(5) Production as a function of water use

Figure 5.1.B Feedback Control Loop of the Characterized Irrigation System Linked to the Equations

Results and Analysis

Calibration. The calibrated simulation of the last 37 years after the construction of the main engineered system included the two main flood disturbances of very strong El Nino events (in 1983 and 1998). For parameter calibration details as well as for designated values as initial conditions of the state variables see Appendix 5.2. The simulated evolution of the cooperation fraction, and the engineered infrastructure performance during the period 1980 – 2016 are shown in figures 5.1.A and 5.1.B. The engineered infrastructure consists of the biggest reservoir in South America with an initial capacity of 789 MCUM, big canals and drainage systems, which was entirely financed by the government for the development of agriculture in the region. The project was planned to be partly self-financed by farmers contributions when stronger capacities and benefits were developed, thus the government has been patient by financing most of the maintenance fee, which is as significant as the size of the engineered project. Farmers' contributions have become progressively more significant, as the fraction of cooperation has increased as shown in figure 5.1.A. Farmers cooperation was affected by the El Nino event of 1998, on which observation from secondary data (ANA 2009, Leonidas 2008) also agrees with the model. Note that in El Niño events cooperation is affected not for moral reasons, but rather for capacity to contribute to the public good, given that most of the farmers lose their production and other goods.

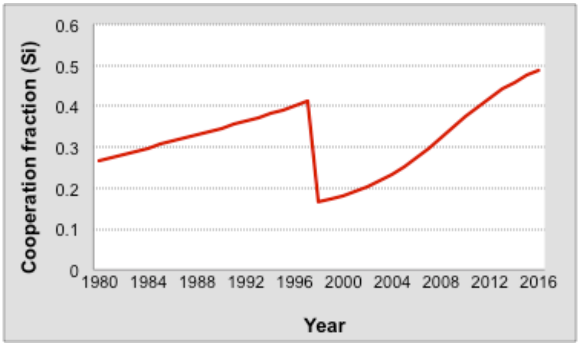


Figure 5.1.A: Simulated cooperation fraction (Si) for upstream and downstream farmers for year 1980 – 2016.

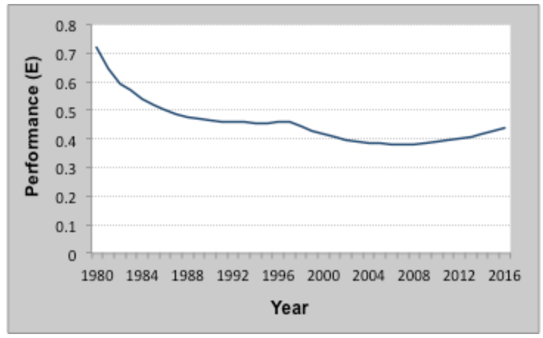


Figure 5.1.B: Simulated engineered constructed performance (E) for years 1980 – 2016.

Another interesting thing to note is that the cooperation fraction of upstream and downstream farmers are exactly the same. An explanation of these results is that with the construction of the reservoir, the system became robust to droughts in the Medio and Bajo Piura sub-basin to the point that in the absence of extreme flood events that damage the infrastructure, there are only few events in which water is scarce (Leonidas, 2008). The decision to keep the equations for differentiating upstream and downstream farmers is based on the interest in providing a model for further analysis on effects on: (1) stronger drought events on this sub-basin (which is beyond the scope of this study), and (2) for analyzing other systems that share the main characteristics proposed in the model for the Peruvian north coast case, such as the Chancay-Lambayeque Basin (Rubinos, 2013), or the San Lorenzo (INRENA, 2008), Chira (ANA, 2009), Motupe, Olmos, La Leche (Garcés-Restrepo, & Guerra-Tovar, 1999), and Jequetepeque (Gómez, L. I., et al., 2007), and to other potential systems regardless of their location.

Figure 5.1.B illustrates the evolution of the past 37 years of the engineered

constructed performance. As we can observe, the performance value for 1980 is close but different to 1 given that the full project was not finished. Some secondary canals and drainage infrastructure were left for its future development. Congruent with the limitations of the system to collect the necessary investment to bring the engineered infrastructure performance to its best possible level, we see how the original performance decreases at a relatively high speed. However, the increase in cooperation, and thus farmers provisioning during the 80s and the early 90s positively affected the engineered constructed performance (slowed the rate of decline), just until the next strong flood event occurred in 1998 to bring down the performance once again. Though, while farmers slowly recuperated from the impact of El Nino, their cooperation increased accordingly and they invested more in the engineered infrastructure, which brought up the performance measure.

Sensitivity Analysis. To address my first research question: "How does public-infrastructure (hard and soft) performance affect collective action in the asymmetric irrigation systems of the Peruvian north coast?" I performed a sensitivity analysis for different initial conditions of "*E*" the engineered infrastructure, and for different values of the parameter "*P*" the probability of enforcing sanctioning mechanisms, to analyze the effects on the cooperation fraction in the system (*Si*).

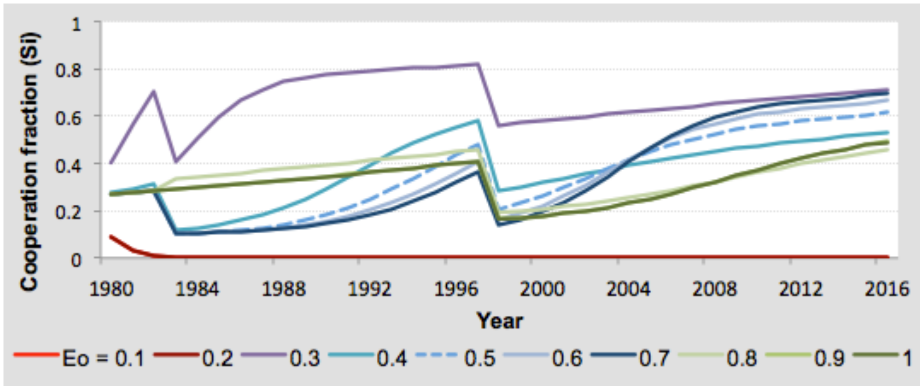


Figure 5.2.A Simulated cooperation fraction (S) for different levels of initial conditions of the engineered constructed performance (Eo)

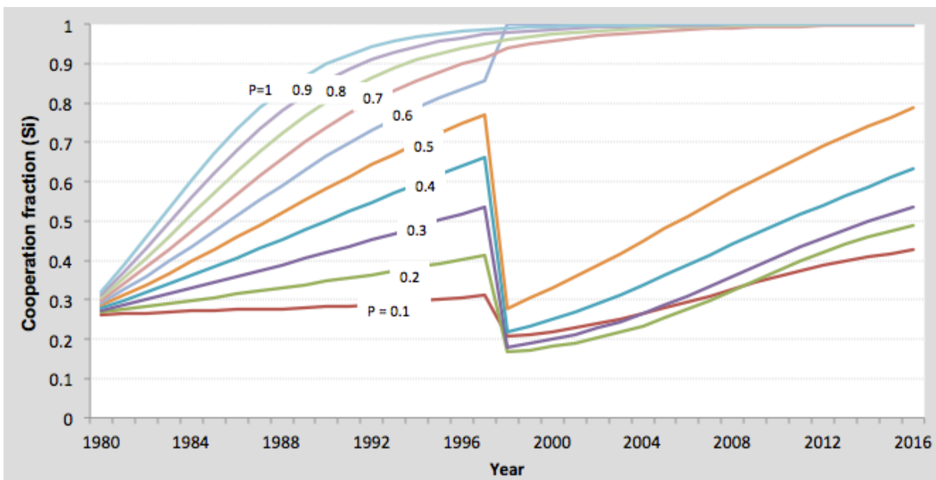


Figure 5.2.B Simulated cooperation fraction (S) for different levels of probability of being sanctioned (σ)

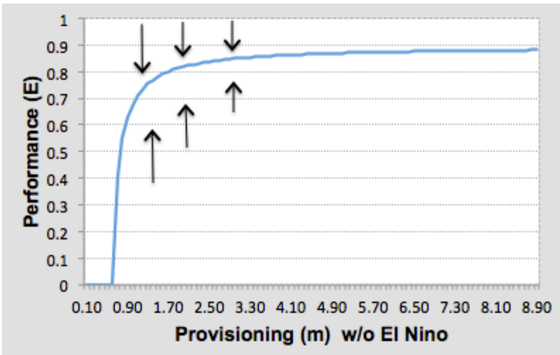
Figure 5.2.A illustrates that there is a minimum of engineered performance that is needed to trigger cooperation. It also illustrates the importance path dependency through the impact of initial conditions on long-term outcomes. The relationship between the initial condition of the engineered performance and the results of cooperation is not always positive. As we can see in figure 5.2.A an increase in E_o from 0.2 to 0.3, generates a positive impact in the evolution of cooperation in the system. An increase in E_o from

0.3 to 0.4 however, generates a negative impact in the evolution of cooperation. However, at very high levels of initial conditions of E (from 0.8 and above), since water is less scarce, users have less incentive to cooperate in the system, plus users that do not pay the water fee can equally withdraw water from the system and get as good payoffs as those who cooperate and have priority on water access.

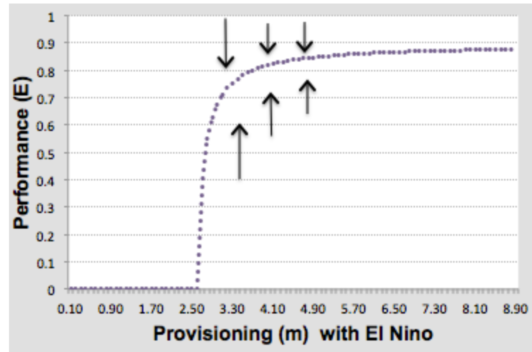
On the other hand, the impact of soft public infrastructure, in this case, sanction enforcement, has a clear direction. Figure 5.2.B clearly shows how when the probability of enforcement increases users are more likely to cooperate. Another interesting thing to note from this graph is the shift of the effect after el Nino event of 1998 when σ moves from 0.5 to 0.6. According to this result when the probability of being sactioned is higher than 0.5 (most likely that a non cooperator will be sanctioned), the cooperation level increases.

Robustness – Fragility Analysis. The second research question refers to the robustness of the system with respect to flood events. I consider a CIS to be *robust* if *"it prevents the ecological systems upon which it relies from moving into a new domain of attraction that cannot support a human population, or that will induce a transition that causes long-term human suffering"* (Anderies et al., 2004 p. 18). A robust system does not necessarily perform at its maximum potential (Csete & Doyle, 2002), but it does remain functional despite internal (e.g., population growth) or external perturbations (e.g., droughts).

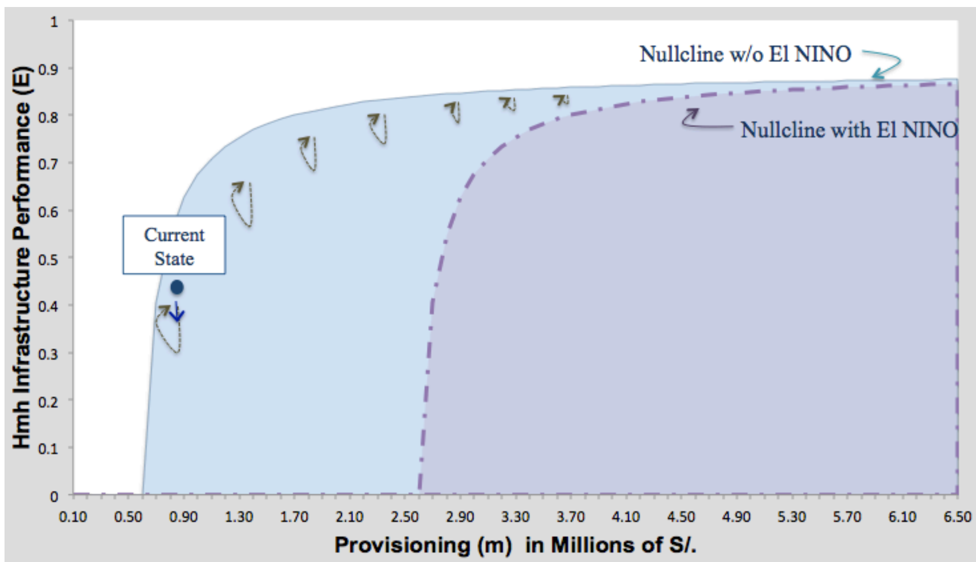
To address this question, I performed an equilibrium and stability analysis of the state variable *E* (engineered constructed performance) with and without flood events with respect to the investment on the maintenance of this infrastructure as a result of the level of cooperation in the system. The analysis is based on the assumption that bigger negative impact of flood events on the performance of the human made hard infrastructure, cause bigger negative impact on society as a whole. In flood events, the reservoir, rivers and canal play an important role to keep water away from the fields and the city. If any of these pieces of infrastructure is washed out, then some water from flood and the river runoff become out of control.



(a)



(b)



(c)

Figure 5.3: Investment in engineered constructed maintenance (m) and its performance (E). Blue continued curve shows the long-term equilibrium for infrastructure performance in the absence of flood events (highlighted in figure (a)), and the purple doted line in the presence of flood events (highlighted in figure (b)). The difference between both curves then, indicates the degree of fragility or robustness of the system to flood events from El Nino phenomenon.

Figure 5.3 shows the required level of annual investment for achieving a stable level (equilibrium) of the public engineered infrastructure in the absence of flood events (each point of the continue blue curve). The blue dot indicates that at the current modeled level of investment even though the infrastructure achieves a level of performance of

0.44, eventually it could achieve a stable equilibrium of 0.6 in the absence of El Nino event. However, since the system is exposed cyclically (though erratically) to flood events, this equilibrium will be eventually disrupted. The purple dashed curve on figure 5.3 shows the required investment for achieving a stable equilibrium under the presence of El Nino events. At a determined level of investment without any El Nino event, the infrastructure performance could reach its maximum level determined by the blue line, but when flood events occur the infrastructure performance is affected proportionally to the difference between its state and the purple dashed curve. Thus in the current situation of investment, el Nino has bigger effects on the infrastructure performance than if the level of investment would be, for example, S/.5 millions. According to this analysis, the model shows that in the current state of the system, the Medio y Bajo Piura is fragile to flood events.

To illustrate the dynamic that figure 5.3 predicts, I performed an analysis of the system under 4 different potential scenarios. Since it is very likely that Piura will be affected by stronger and more frequent El Nino events (Hendriks, 2009) I simulated scenario 1: same intensity of disturbance (17,000 MMC), same frequency (every 15 years); scenario 2: same intensity of disturbance, but more frequent (every 10 years); scenario 3: stronger intensity (18,000 MMC) of disturbance, 15-year frequency; scenario 4: same intensity of disturbance (17,000 MMC), and more frequent (every 10 years). Figures 5.4.A – 5.4.E show how in all four scenarios the system presents similar responses in terms of robustness and in cooperation fraction. Figures 5.4.A and 5.4.B illustrate farmers' net benefits, how they are affected during flood event and how at different speeds, they return to the path of equilibrium. The effect on farmers' net benefits has repercussions in the fraction of cooperation (shown in figure 5.4.C) and in the public infrastructure maintenance investment (shown in figure 5.4.D). As a result, the engineered constructed performance fluctuates below its potential equilibrium (figure 5.4.E). According to these results, the current status of the infrastructures of the systems make the system robust enough to avoid a collapse, but it does not make the system robust enough to prevent human suffering and public infrastructure (hard and soft) relapse when flood events occur.

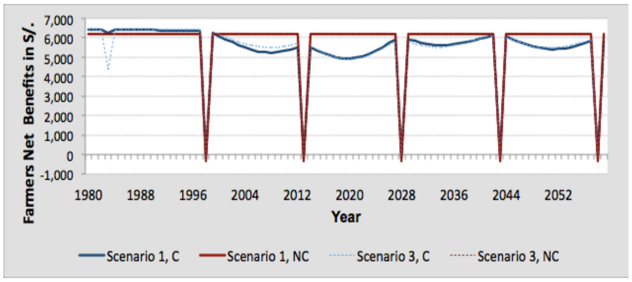


Figure 5.4.A: Farmers projected benefits in two different scenarios *(scenarios 1 and 3, see bellow).*

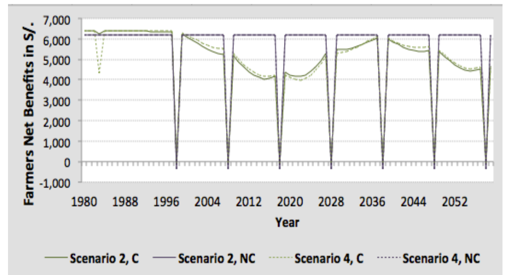


Figure 5.4.B: Farmers projected benefits in two different scenarios *(scenarios 2 and 4, see bellow).*

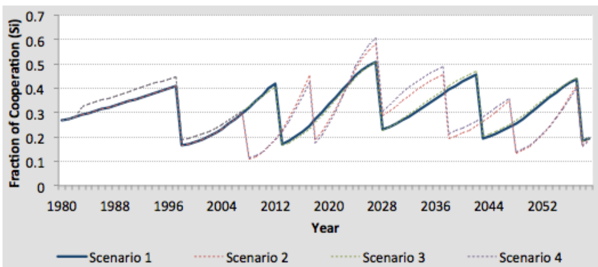


Figure 5.4.C: Projected fraction of cooperation in four different scenarios, see bellow

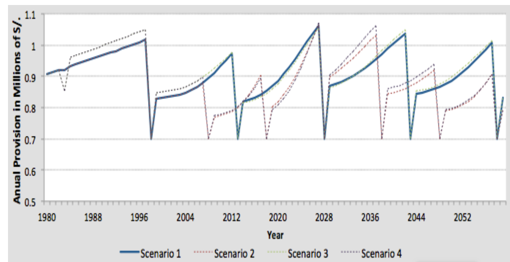


Figure 5.4.D: Projected annual provisioning to the infrastructure maintenance in four different scenarios, see bellow

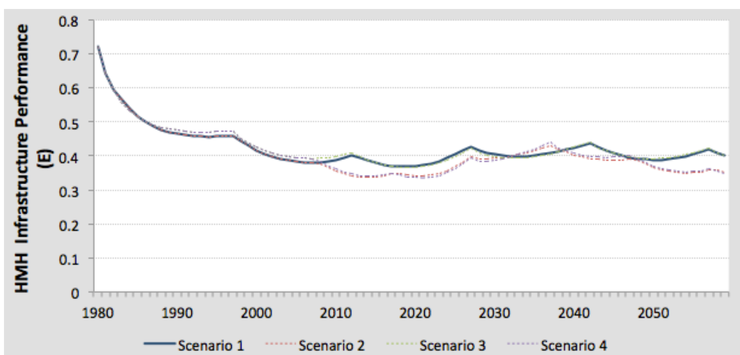


Figure 5.4.E: Projected Infrastructure performance under four different scenarios.

Figure 5.4: Scenario 1: same intensity of disturbance than past events (17,000 MMC), same frequency than past events (every 15 years). Scenario 2: same intensity of disturbance (17,000 MMC), but more frequent (every 10 years). Scenario 3: stronger intensity (18,000 MMC) of disturbance, same frequency (every 15 years). Scenario 4: same intensity of disturbance (17,000 MMC), (more frequent) every 10 years.

Policy Intervention Analysis. In light of the findings of this research so far, the third and last question of this study "What interventions can increase the robustness of the system to extreme flood events?", can become more specific to: how to increase the investment in the public infrastructure to achieve a state where the system is more robust to flood events? The government has stated its intention to withdraw its support in the system progressively. Moreover, since many Peruvian regions are exposed to El Nino and other environmental problems due to climate change, the government presents serious resources limitations whether there is or not, political will to increase its support to a specific system. If the government and users are to work together for a joint intervention to increase the system robustness to flood events, they may want to explore a combination of different policies that affect the long-term self-managing component of the system. For the sake of clarity, I explore the question of potential intervention in an isolated fashion. The option of investing one time only in the engineered constructed system (changing initial condition of this infrastructure) was analyzed previously, and we learnt that it is not very effective given that current state. Investing in soft infrastructure, specifically in enhancing the probability of sanctioning non-cooperative behavior, was on the contrary more effective according to figure 5.2.B. I explore the performance of three different additional strategies to consider.

Increase of users' awareness of the importance of cooperation for water and flood management. Users in the Medio and Bajo Piura have been encouraged to participate in different workshop and seminars where they have learned about the benefits of cooperation. It is difficult to isolate the effect of this policy, however if effective its effect can be translated in the model as if users increase their moral inertia when considering evading water tariff. In this case, ρ the parameter of relative speeds of conversion from cooperator to non-cooperator with respect to the opposite will take different values than 1. Figures 5.5 show how when the value of ρ gets closer to 0, the fraction of cooperators and the impact of the infrastructure performance are more robust to flood events.

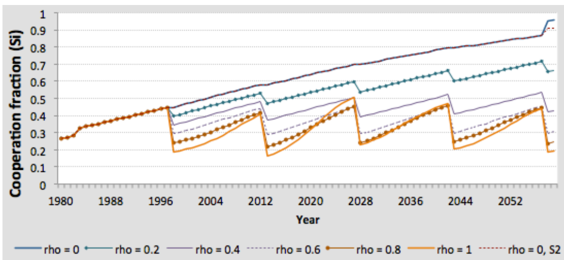


Figure 5.5.A: Projected cooperation fraction under the scenario of similar El Nino events in frequency and intensity as the historical evidence for different levels of moral inertia.

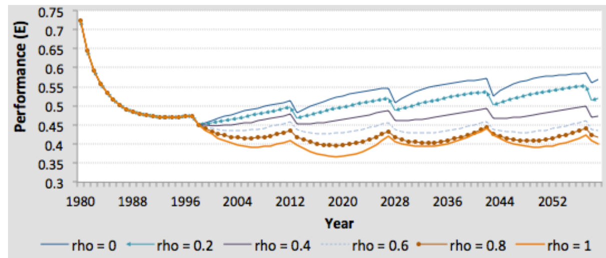


Figure 5.5.B: Projected infrastructure performance trend under the scenario of similar El Nino events in frequency and intensity as the historical evidence for different levels of moral inertia.

Increase in water tariffs. The Water tariff for Bajo and Medio Piura was of 0.003 S/. per m3 in 2016, which is considered as very low by all the reviewed sources (PECHP, 2016, ANA 2009, Leonidas 2008). According to the model, the water tariff would need to increase to around 0.012 to increase the fraction of cooperators to become robust to flood events.

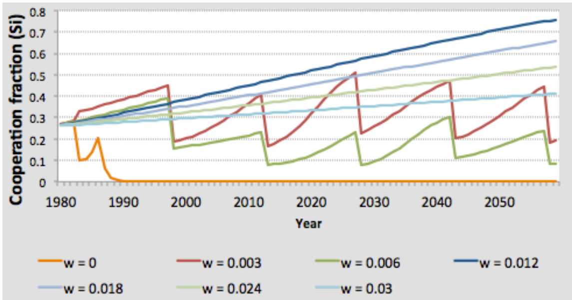


Figure 5.6.A: Projected cooperation fraction under the scenario of similar El Nino events in frequency and intensity as the historical evidence for different levels of water tariffs.

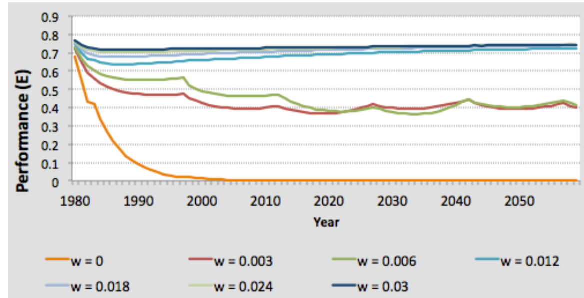
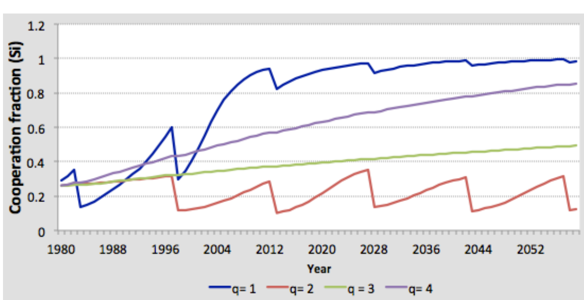


Figure 5.6.B: Projected infrastructure performance trend under the scenario of similar El Nino events in frequency and intensity as the historical evidence for different levels of water tariffs.

Farmers' capacity building with respect to efficient water and other inputs use.

According to a report of the ministery of agricutlure, farmers in the Medio y Bajo Piura sub-basin have an irrigation efficiency of only 35% which, combined with other agricultural practices such as the overuse of fertilizer, or the deficit in drainage processes for soil preservation, causes a low productivity in the sub-basin. According to the model, if farmers improve their farming productivity (e.g. though capacity building), they may become more robust to flood events. Even so, the model shows that it would be necessary to double their productivity (form 1.45 to 3).



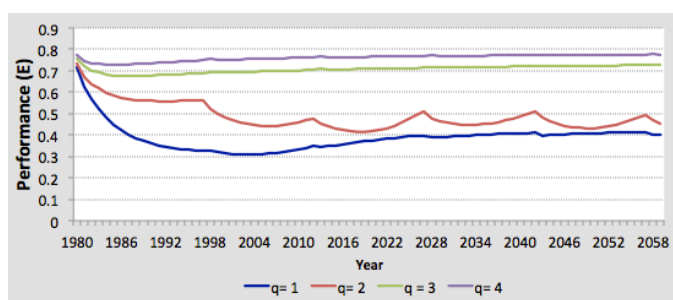


Figure 5.7.A: Projected cooperation fraction under the scenario of similar El Nino events in frequency and intensity as the historical evidence for different levels of rice growing productivity

Figure 5.7.B: Projected infrastructure performance trend under the scenario of similar El Nino events in frequency and intensity as the historical evidence for different levels of rice growing productivity

Conclusion

Environmental disasters have shaped society around the world, sometimes at a very high cost. Given the effects of globalization, especially those related to climate change, many CISs need to be better prepared for natural, and thus unavoidable, disasters. Although the Peruvian north coast has always been exposed to disastrous flood and drought events from El Nino phenomena, it has been predicted that these events will be more intense and more frequent in the future. Understanding the core dynamics of irrigation systems that are critical to protect from damage through flood prevention is one of the aims of this research. To that end, I developed a dynamic model that characterizes the main infrastructures based on field observations of one of the Peruvian north coast systems: Medio y Bajo Piura sub-basin. The model revealed that one-time investments in hard infrastructure may not be the most effective solution since by making a system more robust to a particular disturbance (in this case the reservoir helped prevent the system from suffering from droughts), it increases the fragility of the system to other disturbances (in this case floods). These results are illustrated in figure 5.2.A, which clearly shows how a change in the initial condition of the infrastructure performance from 0.4 (current state) to 0.8 as an example, the system becomes less robust to floods in time. Thus, when the government or other public infrastructure provider invests only one time to increase the hard infrastructure performance (E_o), it does not necessary have a positive effect in the cooperation fraction.

On the other hand, it seems that investing in soft infrastructure (sanctions enforcement in this case) may be more effective. Figure 5.2.B. shows how by increasing the expected sanction to 0.6, which qualitatively can be interpreted as "it is more likely that a farmer will get sanctioned" the system shifts to a sharp increase in collective action. Collective action is very much needed to increase the maintenance of the engineered infrastructure, and thus increase the system's robustness to flood events as shown in Figure 5.3. The model also reveals that an increase to a constant level of investment for the engineered infrastructure maintenance can increase the robustness of the system to floods. Figure 5.3 displays the long run equilibria and Figures 5.4 its simulated dynamics. In any potential scenario, the proposition to increase the robustness of the system is the same: It is necessary to increase the investment in a regular maintenance of the engineered infrastructure. The easy solution is to ask to the government an increase in the budget for this system, but reality shows that limited resources can offset political will. Different other strategies, namely stablishing a strong social norm for participating in prevention infrastructure (soft and hard), increase of water tariffs and farming productivity, for increasing the investment in the engineered infrastructure were explored. A combination of all or some of them can be targeted to increase the robustness of the system.

The model is based on some assumptions such as a fixed number of users and a constant water flow in the absence of flood events. A relaxation of one or both of those assumptions may reveal problems of water scarcity that most likely will change the dynamics of the system. This was not the scope of this research, though future research could focus on how the relaxation of these assumptions affects the system to inform for policy makers to increase the robustness of the system to droughts. Another assumption of the model is the homogeneity of users and crops. I used the most grown crop in the basin (rice) for the model calibration, though there are studies (such as Loyola & Orihuela (2010)) that show how the agriculture activity can be affected also by changes in temperature, which is also another threat from climate change. Rice is a low sensitive crop to changes in temperature and flood events. However, other crops that are grown in the system may be more sensitive to high temperatures and floods. Future research can also explore the effect of temperature in crop productivity.

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CHAPTER 6

RESEARCH FINDINGS SYNTHESIS

In this dissertation I address two related issues of particular concern for the sustainability of Coupled Infrastructure Systems (CIS): how to overcome social dilemmas to avoid over-appropriation incentives, poverty traps and critical conflicts; and how to design robust system to environmental shocks. How these two issues are connected is still unclear, and more research is needed to identify if one is necessary and/or sufficient for the other. However, my findings show that collective action might be needed for improving levels of robustness of CIS to potential shocks.

I started this dissertation with a critical literature review of Elinor Ostrom's institutional design principles for successful collective action. I performed an analytical literature review of 64 studies that analyzed Ostrom's design principles in real world case studies, and others that did not explicitly mentioned the design principle but that included an institutional analysis on their study. I looked for clarity of each DP, on desired outcomes intended by each DP, and for circumstances found in the field or in research that suggest a direction for the refinement of the DPs. I recommend referring to the DPs in a more specific approach by subdividing them in components.

Later, in Chapter 3, I used the identified DPs components to code 28 irrigation systems that were previously studied by other authors. I also coded for contextual variables (biophysical and ethnographic) to look for conjoint causation of a desired outcome (an indicator of levels of over-appropriation, poverty and conflicts in the system). After carrying out this meta-analysis, I found that particular combinations of the variables related to population size, countries corruption, the condition of water storage, monitoring of users behavior, and involving users in the decision making process for the commons governance, were sufficient to obtain the desired outcomes.

In the two last studies of this dissertation, I switched my focus to Robustness analysis of CIS to environmental threats. I studied, with the use of two different methods, the Peruvian Piura Basin: a CIS that has been exposed to environmental shocks for decades. First, I used secondary and primary data to carry out a longitudinal study using as guidance the robustness framework, and different hypothesis from prominent collapse theories to draw potential explanations. Collapse theories revealed many fragilities in the Piura Basin, and one particular strength: farmers have shown an increase in their awareness and capacities to collectively work on prevention savings and public infrastructure provisioning. The effort is recognized, but it is still not enough to avoid being negatively affected by floods from El Niño events. Since it is the public infrastructure what buffers the impact from flood events in the Piura Basin, it is likely that by investing in developing the farmers collective action capacities, policymakers can help to increase the robustness of the system to flood events.

In Chapter 5, I developed a dynamic model to 1) understand the core dynamics of the systems with respect to the relationship between public-infrastructure and collective action, 2) to understand how robust is the irrigation systems to extreme flood events, and 3) to explore potential interventions to increase the robustness of these systems to flood events. I calibrated the model to predict behaviors and results in the Piura Basin. The model revealed that for the Piura Basin, collective action is very much needed to increase their robustness to flood events. Given the limitations of the governmental capacity to make high and regular investment in the system, the hard and public infrastructure is damaged in El Niño episodes, and significant human suffering is experiences in the basin. An improvement of farmers; collective action can change those results. The model shows, how at the current situation it is more effective to invest, if only investing one isolated time instead of in a regular basis, in rules enforcement, than in the improvement of the physical infrastructure (e.g. reservoir).

With the use of different method I was able to study CIS from different angles while addressing different, but related questions. From the review of the findings of individual chapters, I highlight first, the need for theoretical clarity and specificity to move forward on theory build of collective action. In this dissertation I have made some suggestions about the direction of the specificity for the DPs, but most important that those suggestions. In second place, it is easy to visualize the large research agenda, when we understand the need to find the potential recipes for given contextual factors. Policymakers, especially in developing countries, face limited resource for governance. Science can enormously contribute to governance challenges by enhancing the understanding of which rules and principles are more effective for a given type of CIS. The last remark is with respect to the robustness and collective action theoretical and practical interconnection. According to the findings in this dissertation, collective action is needed to increase the robustness of the Piura Basin to flood events. However, whether if this is true for other CIS, or not, is still unclear. Further research is needed to explore the interconnection between robustness and collective action. I conclude this dissertation with the satisfaction of having addressed relevant questions for sustainability science, but with and increased curiosity about the commons governance puzzle.

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APPENDIX A

LIST OF CODED CASES FOR CHAPTER 3

Case N	Country	Case Name	Reference
1	Haiti	Dubre´	Boyer, M., Speelman, S., & Van Huylenbroeck, G. (2011). Institutional analysis of irrigation management in Haiti: a case study of three farmer managed schemes. Water Policy, 13(4), 555-570. Starts in Page 558 -
2	China	S - Zhuolu	Wang, X., Otto, I. M., & Yu, L. (2013). How physical and social factors affect village-level irrigation: An institutional analysis of water governance in northern China. Agricultural water management, 119, 10-18.
3	China	Zhuolu - SG only surface water	Wang, X., Otto, I. M., & Yu, L. (2013). How physical and social factors affect village-level irrigation: An institutional analysis of water governance in northern China. Agricultural water management, 119, 10-18.
4	China	Zhuolu - SG s&gw	Wang, X., Otto, I. M., & Yu, L. (2013). How physical and social factors affect village-level irrigation: An institutional analysis of water governance in northern China. Agricultural water management, 119, 10-18.
5	Japan	Nishikamb ara	Sarker, A., & Itoh, T. (2001). Design principles in long-enduring institutions of Japanese irrigation common-pool resources. Agricultural Water Management, 48(2), 89-102.
6	Ethiopia	Atsbi Wemberta	Deribe, R. (2008). Institutional Analysis Of Water Management On Communal Irrigation Systems: The Case Of Atsbi Wemberta District In Tigray Region And Ada'a District In Oromiya Region, Ethiopia (Doctoral Dissertation, Addis Ababa University).
7	Ethiopia	Ada'a Woreda	Deribe, R. (2008). Institutional Analysis Of Water Management On Communal Irrigation Systems: The Case Of Atsbi Wemberta District In Tigray Region And Ada'a District In Oromiya Region, Ethiopia (Doctoral Dissertation, Addis Ababa University).
8	Taiwan	Chianan IA	Lam, W. F. (1996). Institutional design of public agencies and coproduction: a study of irrigation associations in Taiwan. World development, 24(6), 1039-1054.
9	Peru	Lurin Sayoc	Mitchell, W. P. 1977. Irrigation Farming in the Andes: Evolutionary Implications. St. Martin's Press, New York, USA. 36-59., Mitchell, W. P. 1976. Irrigation and Community in the Central Peruvian Highlands. American Anthropologist. 78:25-44. DOI https://seslibrary.asu.edu/node/68
10	Mexico	Tramo Diaz Ordaz	Downing, T. E. 1974. Irrigation and Moisture Sensitive Periods: A Zapotec Case. University of Arizona Press,Tucson, AZ, USA. Chapter 10: 113-122. DOI https://seslibrary.asu.edu/node/37
11	Philippine s	Agcuyo	de los Reyes, R. P. 1980. Agcuyo Irrigation System. Institute of Philippine Culture, Quezon City, Philippines. Chapter 6: 42-48. DOI https://seslibrary.asu.edu/node/36
12	Argentina	San Juan Canal 9	Gonzalez-Aubone, F., Miranda, O., Montenegro, F., & Andrieu, J. (2014). Analizando la modernizacion en regadios tradicionales del oeste argentino. / Gestion del agua para riego de uso comun (RUC): la busqueda de un desempeno eficiente y sostenible a traves de un enfoque institucinoal. El caso de la provincia de San Juan, Argentina
13	Peru	Chancay Lambayequ e	Rubinos, C. (2013). Institutional Analysis of Water Management for Agriculture in the Chancay-Lambayeque Basin, Peru. Arizona State University. DOI https://seslibrary.asu.edu/node/273

14	Tanzania	Mara River Basin	Majule, A. E. (2010). Towards sustainable management of natural resources in the Mara river basin in Northeast Tanzania. Journal of Ecology and the Natural Environment, 2(10), 213-224.
15	Mali	The Office Du Niger	Vandersypen, K., Verbist, B., Keita, A. C., Raes, D., & Jamin, J. Y. (2009). Linking performance and collective action—the case of the Office du Niger Irrigation Scheme in Mali. Water resources management, 23(1), 153-168.
16	Australia	The Upper and Lower Naomi groundwate r source	Ross, A., & Martinez-Santos, P. The challenge of collaborative groundwater governance: four case studies from Spain and Australia.
17	Australia	The Lower Murray Groundwat er Source	Ross, A., & Martinez-Santos, P. The challenge of collaborative groundwater governance: four case studies from Spain and Australia.
18	Spain	The Mancha Occidental	Ross, A., & Martinez-Santos, P. The challenge of collaborative groundwater governance: four case studies from Spain and Australia.
19	Spain	The Campo de Montiel Aquifer	Ross, A., & Martinez-Santos, P. The challenge of collaborative groundwater governance: four case studies from Spain and Australia.
20	Egypt	Al-Bayda	Abdo, A. Understanding Farmers' Adaptation to Water Scarcity. IWMI Research Report
21	Indonesia	Bali	Lorenzen, S., & Lorenzen, R. P. (2005, August). A case study of Balinese irrigation management: institutional dynamics and challenges. In Second Southeast Asia Water Forum. Nusa Dua, Bali.
22	Israel	Hefer valley	Manor, S & Hagali, Z. (2002). Case Study from Israel. Survey on Irrigation Modernization. The Hefer Valley Water Users Association. FAO
23	Tanzania	Kiru Valley	Said, S. (2006). Irrigation in Africa: Water conflicts between large-scale and small-scale farmers in Tanzania, Kiru Valley.
24	India	Tambrapar ani	Brewer, J. D., Sakthivadivel, R., & Raju, K. V. (1997). Water distribution rules and water distribution performance: a case study in the Tambraparani irrigation system (Vol. 12). IWMI.
25	Tanzania	Usangu Basin	Cleaver, F. D., & Franks, T. R. (2005). How institutions elude design: river basin management and sustainable livelihoods.
26	USA	Taos Valley	Cox, M., & Ross, J. M. (2011). Robustness and vulnerability of community irrigation systems: The case of the Taos valley acequias. Journal of Environmental Economics and Management, 61(3), 254-266. ISO 690
27	Uganda	Ruhaama County	McPartlon, Emily, "Testing Ostrom: an Analysis of Water User Commi;ees in Uganda" (2016). Master's eses. Paper 180.
28	Peru	Piura	Rubinos, Cathy (working paper) "Robustnes - Fragility Trade-offs: The Lower and Middle Piura Basin and El Niño Events"

APPENDIX B

CODING SCHEME FOR CHAPTER 3

(GOOGLE FORM)

Coding Form

Coder's Name

Your answer

Country

Your answer

Case Name

Your answer

1. Type of Irrigation System (users withdraw waters from...)
River or Canal
Groundwater
Mixed

Notes 1
Your answer

Outcome Variables

2. Are there conflicts in the system?
Yes, significant conflicts
Yes, but nothing to worry about
No
There is not enough information to answer

Notes 2
Your answer

3. If YES. Are these conflicts among the community or with other users outside the community?
Among the community
With other users
NA (Question 2 was" NO")
There is not enough information to answer

Notes 3
Your answer

4. Are rules equal for every users?

Yes
NO
There is not enough information to answer

Notes 4
Your answer
☐

5. Rule compliance: appropriation rules
Everyone or almost everyone follows appropriation rules
Around half of users follow appropriation rules
Few people follow appropriation rules
There is not enough information to answer

Notes 5
Your answer
☐

6. Rule compliance: provisioning rules (e.g pay tariffs, canal maintenance work, etc.)
Everyone or almost everyone follows provisioning rules
Around half of users follow provisioning rules
Few people follow provisioning rules (significant presence of theft)
There is not enough information to answer

Notes 6
Your answer
☐

7. Distribution Infrastructure Condition (e.g. Canal)
Well maintained (e.g. level of efficiency more than 60%)
Somehow maintained, (e.g. level of efficiency higher than 50% but less than 60%)
Poorly maintained (e.g. level of efficiency 50% or less)
There is not enough information to answer

Notes 7
Your answer
☐

8. Production Infrastructure Condition (e.g. Reservoir)
Well maintained (e.g. level of efficiency more than 60%)
Somehow maintained, (e.g. level of efficiency higher than 50% but less than 60%)
Poorly maintained (e.g. level of efficiency 50% or less)
NA (e.g. no reservoir)
There is not enough information to answer

Notes 8
Your answer
☐

9. Environtmental Degradation (e.g. contamination / salinity, forest reduction)
The text mentions that there are no degradation problem
Some degradation problem is present
Big degradation problems
No degradation issues are mentioned in the text

Notes 9
Your answer
☐

10. Over appropriation of the community as a whole (there must be a minimum of water in the system)
Overused
Balanced
The system use less water of the maximum total water allowed for sustainability reasons
There is not enough information to answer

Notes 10
Your answer
☐

46. Is there a perception of scarcity for most users?
Yes
No
There is not enough information to answer

Notes 46
Your answer
☐

11. Is a group's payoffs being negatively affected by others?
Yes
No
There is not enough information to answer

Notes 11
Your answer
☐

33. Do users have governmental support (e.g. subsidies) or Donors?
1) Yes, farming subsidies
2) Subsidies for water use
3) Donors
a combination of 1, 2 or 3
No
There is not enough information to answer

Notes 33

Your answer

12. Is the system self-sustained? (If there is an external entity -e.g gov, NGO- that gives significant help, then NO)
Yes
No
There is not enough information to answer

Notes 12
Your answer

13. Do you think this case is successful ? (Success: No over appropriation, AND no critical conflicts, AND Self-sustained systems, AND poverty is not a problem)
Yes
No

Notes 13
Your answer

Institutions

14. Is it clear who are the users of the resource and their rights are recognized?
Yes
No
There is not enough information to answer

Notes 14
Your answer

15. Are the borders and water sources that the community can use clearly defined?
Yes
No
There is not enough information to answer

Notes 15
Your answer

16. Do operational rules (not necessary rules in use) consider a proportional equivalence between benefits and costs?
Yes
No
There is not enough information to answer

Notes 16
Your answer

17. Are appropriation rules flexible to fit local conditions (ecology and culture)?
Yes
No
There is not enough information to answer

Notes 17
Your answer

18. Do Appropriators think rules are fair?
Yes
No
There is not enough information to answer

Notes 18
Your answer

19. Is there a space (physical or not) to express users' needs and concerns to the ones that make decision and these are actually taken into account?
Yes
No
There is not enough information to answer

Notes 19
Your answer

20. Do users participate to elect their leaders?
Yes
No
There is not enough information to answer

Notes 20
Your answer

21. Has there been collective action to change rules?
Yes
No
There is not enough information to answer

Notes 21
Your answer

☐

22. Does someone monitor the resource appropriation?
Yes
No
There is not enough information to answer

Notes 22
Your answer
☐

23. Are monitors of water appropriation accountable? Is it well-enforced (users actually believe that they can get caught when getting more of their share)?
Yes
No
There is not enough information to answer

Notes 23
Your answer
☐

24. Do users pay water fees
Everyone or almost everyone
Around half of users
Few users pay water fees
There is not enough information to answer

Notes 24
Your answer
☐

25. Do they keep records of the water level in the river, reservoir or groundwater?
Yes
No
There is not enough information to answer

Notes 25
Your answer
☐

26. Do they register the conditions of the hard human made public infrastructure (canals, reservoir, etc.)?
Yes
No
There is not enough information to answer

Notes 26
Your answer

27. Do they have graduated sanctions and this are known by users?
Yes
No
There is not enough information to answer

Notes 27
Your answer

28. can you infer that users believe that they can get caught and be fairly sanctioned if they do not cooperate?
Yes
No
There is not enough information to answer

Notes 28
Your answer

29. Is there at least one shared space/area for conflict resolution that it is being used?
Yes
No
There is not enough information to answer

Notes 29
Your answer

30. Is it true that: Appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities are well organized in multiple layers of nested enterprises and they don't conflict with each other?
True
False
There is not enough information to answer

Notes 30
Your answer

31. Transparency of management. Do users know management details?
Yes
No
There is not enough information to answer

Notes 31

Your answer

32. Are Non-Governamental Organizations involved?
Yes
No
There is not enough information to answer

Notes 32
Your answer

34. When was the association created?

Your answer

35. If there was a perturbation are they still in the process of adjusting?
There are no perturbations mentioned
They overcame all perturbations
They did not overcome at least one perturbation (still in process of finding a solution)
There is not enough information to answer

Notes 35
Your answer

36. Type of governance
Top Down
Co-managed (it was before top-down)
Co-manged (it was before self-managed)
Self managed

Notes 36
Your answer

37. year of research / field work

Your answer

38. Which is the Country indicator of Corruption for the year researched? (Indicator)

Your answer

Biophysical Variables

39. Can users see most of other users water appropriation
Yes
No

There is not enough information to answer

Notes 39
Your answer

40. Are crops also watered with rain?
Yes
No
There is not enough information to answer

Notes 40
Your answer

41. Are users growing commodities? (rice, maize, corn, sugar, cotton, grains, Coffee, etc.) – low prices)
Yes, Only commodities
Yes, but also other crops (e.g. vegetables)
No
There is not enough information to answer

Notes 41
Your answer

42. Are they growing high water demanding crops? (rice, sugar cane, nuts, corn, cotton, tomato, alfalfa, almond)
Yes
No
There is not enough information to answer

Notes 42
Your answer

43. Technology to irrigate fields
Drip Irrigation
Sprinklers
Furrow
There is not enough information to answer

Notes 43
Your answer

44. Is the human made hard infrastructure very technical and expensive to maintain?
Yes

No
There is not enough information to answer

Notes 44
Your answer
☐

45. Do they store water in a way? (Reservoir, dam, tanks, wells)
Yes
No
There is not enough information to answer

Notes 45
Your answer
☐

47. Is the system asymmetric because of biophysical characteristics? (Upstream – downstream)
Yes
No
There is not enough information to answer

Notes 47
Your answer
☐

48. Is the weather predictable?
Very predictable
Not too much
Unpredictable
There is not enough information to answer

Notes 48
Your answer
☐

49. Is the system exposed to natural disaster?
Yes, very often
Yes, not often
No
There is not enough information to answer

Notes 49
Your answer
☐

50. Land condition
Fertile

low levels of - Fertile (e.g salinization problems)
some problems but it´s ok
There is not enough information to answer

Notes 50
Your answer

51. How big in Km or Ha (total and irrigated) is the total area of the system?

Your answer

Ethnographics and others

52. Is there trust among users?
Yes
No
There is not enough information to answer

Notes 52
Your answer

53. Do users trust their leaders?
Yes
No
There is not enough information to answer

Notes 53
Your answer

54. Are users homogenous?
Yes
No
There is not enough information to answer

Notes 54
Your answer

55. Is the number of users changing (significantly)?
Yes, growing
Yes, decreasing
No
There is not enough information to answer

Notes 55
Your answer

☐

56. Level of education of most of users
Primary school
High school
Technical career
Professional
There is not enough information to answer

Notes 56
Your answer
☐

57. Is it mostly subsistance agriculture or cash crops?
Mostly Subsistance
Mostly Cash Crops
An even combination
There is not enough information to answer

Notes 57
Your answer
☐

58. User's knowledge of Farming Practices
low
moderate
high
There is not enough information to answer

Notes 58
Your answer
☐

59. Farmers dependence on Agriculture
high (e.g. more than 60%)
medium (e.g. between 40% and 60%)
low (e.g. less than 40%)
There is not enough information to answer

Notes 59
Your answer
☐

60. Do they have information about the behavior of other users with regards to public infrastructure provision (if users contributed or not)?
Yes
No
There is not enough information to answer

Notes 60

Your answer

61. do they have a good level of market integration?

Yes (e.g they trade their products outside the community?)

No (e.g. roads are bad, high transportation costs)

There is not enough information to answer

Notes 61

Your answer

62. How many users are there in the system?

Your answer

SUBMIT

Never submit passwords through Google Forms.

APPENDIX C

CODED CASES FOR CHAPTER 3

Case	NonOapp	NoFights	NoPoverty	Env Degradation	SuccessFz	DP1USERS	DP1Borders	Bccongr	Elect	RecCondSES
Dubre	1	0	1	1	0.75	1	1	1	1	1
SZhuolu	1	1	0	1	0.75	1	0	0	0	1
ZhuoluSGSW	1	1	1	1	1	1	1	1	99	1
ZhuoluSGSAGW	1	1	1	1	1	1	1	1	1	0
Nishikambara	1	1	1	1	1	1	1	1	1	1
Wemberta	1	0	0	0	0.25	1	1	1	1	1
Woreda	0	1	1	0.45	0.6125	1	1	1	1	1
Chianan	1	0	0	1	0.45	1	1	0	1	1
Lurin	0	0	1	1	0.45	1	1	1	1	1
DiazOrdaz	1	0	1	1	0.75	1	1	1	99	1
Agcuyo	1	1	1	1	1	0	0	1	1	1
SanJuan	1	1	1	1	1	1	0	1	1	1
ChancayLambayeque	1	0	0	0.45	0.3625	0	0	0	1	1
Mara	0	1	0	0	0.25	1	0	0	1	0
Niger	1	0	1	1	0.75	1	1	0	0	0
Naomi	1	1	1	1	1	1	0	0	1	1
Murray	1	1	1	1	1	1	1	0	0	1
Mancha	1	0	1	0	0.45	1	0	0	0	1
Montiel	0	1	1	0.45	0.6125	1	1	1	0	1
AlBayda	1	0	0	0.45	0.3625	0	1	0	99	1
Bali	0	1	0	0.45	0.3625	1	1	1	99	0
Hefer	1	1	1	1	1	1	1	1	1	1
Kiru	1	0	0	0	0.25	0	0	1	1	0
Tambraparani	0	0	0	0.45	0.1125	0	0	0	1	1
Usangu	1	1	0	1	0.75	0	0	0	1	0
Taos	0	1	1	1	0.75	1	0	1	1	1
Ruhaama	1	1	0	0.45	0.6125	0	1	0	1	1
Piura	0	0	1	0	0.25	1	1	1	0	1

Case	ColAct	confres	Monitoring	Maccount	Gradsanc	SanctEnff	Transparency	Polycent	Gwater
Dubre	1	1	1	1	1	0	0	0	0
SZhuolu	0	0	1	99	0	0	0	0	0
ZhuoluSGSW	1	1	1	1	0	0	0	1	0
ZhuoluSGSAGW	1	1	1	1	1	1	1	1	0.6
Nishikambara	1	1	1	1	0	1	1	1	0
Wemberta	1	1	0	0	1	1	99	1	0
Woreda	1	1	1	1	1	1	1	1	0
Chianan	1	1	1	1	99	1	1	1	0
Lurin	1	1	1	1	0	1	1	0	0
DiazOrdaz	1	1	1	0	0	0	1	1	0
Agcuyo	1	1	1	0	1	0	99	1	0
SanJuan	1	1	1	1	0	1	1	0	0.6
ChancayLambayeque	1	0	0	0	0	0	99	0	0
Mara	1	0	1	0	0	0	0	0	0
Niger	1	1	0	99	0	0	0	1	0
Naomi	0	1	1	0	99	0	1	1	1
Murray	0	1	1	1	99	1	0	1	1
Mancha	1	0	1	1	0	1	1	0	1
Montiel	1	1	0	0	99	0	99	1	1
AlBayda	1	1	1	1	99	1	99	0	0
Bali	1	0	1	0	99	0	99	1	0
Hefer	1	1	1	1	99	1	1	1	0.6
Kiru	0	0	1	1	99	1	1	0	0.6
Tambraparani	0	1	0	0	1	0	99	0	0.6
Usangu	1	1	0	0	1	0	0	0	0
Taos	1	1	0	0	1	0	99	1	0.6
Ruhaama	1	1	1	1	1	1	1	0	1
Piura	1	1	1	1	1	1	0	1	0

Case	NGOs	Perturbation	freqpert	Envpert	Wpredic	corrup	Visib	pdinfo	SelfSust
Dubre	0	0	0	0	0.4	1.6	1	99	0
SZhuolu	0	0	0	0	1	3.6	0	0	1
ZhuoluSGSW	0	0	0	0	1	3.6	0	1	1
ZhuoluSGSAGW	0	0	0	0	1	3.6	1	1	1
Nishikambara	0	0	0.4	1	99	6	0	1	1
Wemberta	1	1	0	0	0	2.4	99	1	1
Woreda	1	1	0	0	0	2.4	1	1	1
Chianan	0	1	0	0	99	4.98	1	99	0
Lurin	0	0	0	0	0.4	3	99	1	1
DiazOrdaz	0	0	1	1	0	3.18	99	99	1
Agcuyo	0	1	1	1	99	2.77	1	1	1
SanJuan	0	1	1	1	1	3.4	99	1	0
ChancayLambayeque	0	1	0.4	1	0.4	3.8	0	99	1
Mara	1	1	1	1	0.4	2.7	1	0	0
Niger	0	0	0	0	99	2,8	99	1	1
Naomi	0	1	1	1	0.4	8.7	0	99	0
Murray	0	1	1	1	0.4	8.6	0	1	1
Mancha	0	1	1	1	1	6.5	0	1	1
Montiel	0	1	1	1	1	6.5	1	1	1
AlBayda	0	0	0	0	0	3.2	1	99	1
Bali	0	1	0	0	99	2.2	1	1	1
Hefer	0	1	1	1	99	6.1	99	1	1
Kiru	1	1	1	1	0	2.9	0	99	1
Tambraparani	0	0	0	0	1	2.8	99	99	1
Usangu	1	0	0	0	99	2.9	0	1	0
Taos	0	1	1	1	0.4	7.5	1	1	1
Ruhaama	1	1	0	0	1	2.5	0	99	1
Piura	1	1	1	1	0	3.5	0	0	0

Case	Irrigdep	commond	cashcrop	Agdepend	Mktintg	cropwdem	Tech	exppubinf	Fair
Dubre	0	1	99	99	99	1	0	0	1
SZhuolu	1	0.6	99	1	0	0	99	99	0
ZhuoluSGSW	1	0.6	99	0.6	1	0	99	0	1
ZhuoluSGSAGW	1	0.6	99	99	1	0	99	0	1
Nishikambara	1	1	99	99	99	1	99	99	1
Wemberta	0	0	0.45	1	0	0	0	0	99
Woreda	0	0	1	1	0	0	0	0	99
Chianan	0	1	99	99	99	1	0	99	99
Lurin	0	1	0	1	1	0	0	0	99
DiazOrdaz	0	1	99	99	99	0	0	0	99
Agcuyo	0	1	99	99	0	1	0	1	99
SanJuan	1	0	1	99	1	0	1	1	0
ChancayLambayeque	1	0.6	1	1	1	1	0	0	0
Mara	0	1	0	1	0	1	0	0	0
Niger	0	1	0.45	1	99	1	0	0	0
Naomi	0	0.6	1	1	1	1	0.6	0	0
Murray	0	0.6	1	1	1	1	99	99	1
Mancha	1	0	1	1	1	0	99	99	0
Montiel	1	0	1	1	1	0	0.6	99	1
AlBayda	1	0.6	1	0.6	1	1	0	0	0
Bali	1	1	1	0.6	1	1	99	99	0
Hefer	1	0	1	99	1	1	1	1	1
Kiru	0	0.6	1	1	99	1	0	1	0
Tambraparani	0	0.6	1	1	1	1	0	99	0
Usangu	0	99	99	1	0	99	99	99	0
Taos	1	99	1	0.6	1	99	99	99	1
Ruhaama	1	99	99	1	99	99	1	1	1
Piura	1	0.6	1	1	1	1	0	1	1

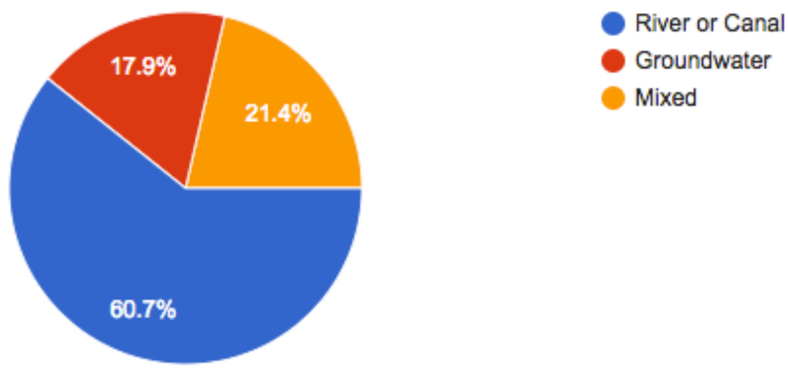
Case	Homog	sizephys	DistCond	ProdCond	trustothers	Trustlead	Popsize	Subs	Asymm
Dubre	99	80	0.55	1	1	1	249	0.6	1
SZhuolu	1	307	0	1	99	0	853	0.6	1
ZhuoluSGSW	1	133	0	1	99	99	344	0.6	0
ZhuoluSGSAGW	99	10	1	1	1	1	20	0.6	0
Nishikambara	99	19103	99	99	1	1	14199	0.8	1
Wemberta	1	221	99	0	1	1	1855	0.8	1
Woreda	1	960	0	0	99	1	2059	1	1
Chianan	1	78113	99	99	99	1	99	0.8	1
Lurin	99	150	99	99	99	1	2500	0	1
DiazOrdaz	0	150	0	0	0	99	4000	0	1
Agcuyo	0	6	0	0	0	0	50	0	1
SanJuan	99	120	0.55	0.55	99	99	600	0.8	1
ChancayLambayeque	0	MIC	0	0.55	99	0	15000	0	1
Mara	0	481250	0	0	0	0	1368602	1	1
Niger	99	20736	0.55	0.55	99	0	6184	0	1
Naomi	99	4200000	99	1	0	99	550	0.8	0
Murray	0	1700000	99	1	99	0	200	0.8	0
Mancha	0	150000	99	0	1	1	15000	0.8	0
Montiel	1	8000	99	1	0	0	100	0.8	0
AlBayda	0	1764	99	1	1	1	99	0.8	1
Bali	0	738	1	1	0	0	99	0	1
Hefer	0	8000	1	1	1	1	2800	0.8	99
Kiru	0	2040	0	99	1	1	6000	1	1
Tambraparani	0	40710	0	0	0	99	3000	0	1
Usangu	0	2200000	99	99	0	0	500000	1	1
Taos	0	40000	99	99	1	1	2500	0	1
Ruhaama	99	3000	0	0	1	1	99	0	0
Piura	0	48000	1	0	99	1	75176	0.8	1

APPENDIX D

DESCRIPTIVE STATISTICS FOR CHAPTER 3

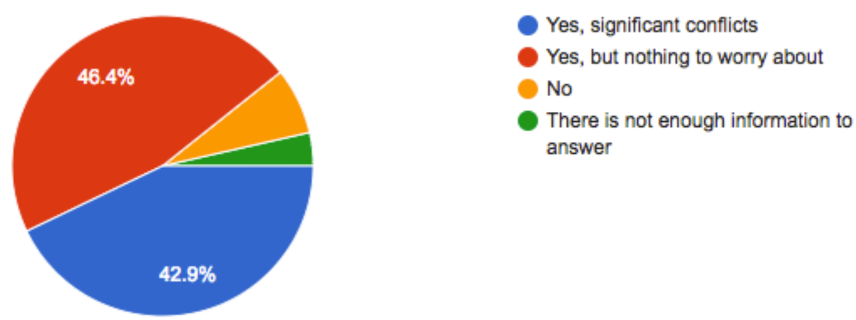
1. Type of Irrigation System (users withdraw waters from...)

28 responses



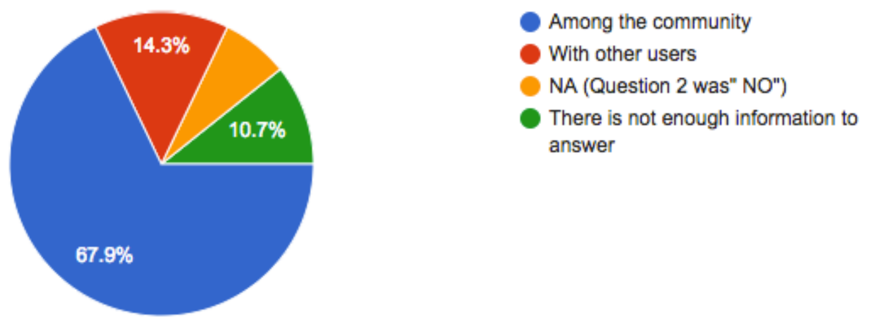
2. Are there conflicts in the system?

28 responses



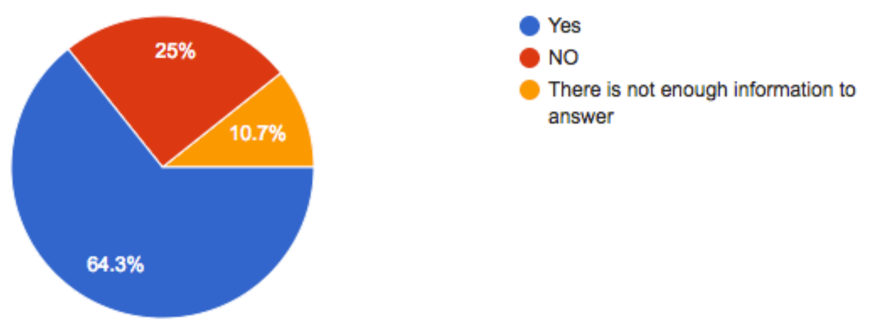
3. If YES. Are these conflicts among the community or with other users outside the community?

28 responses



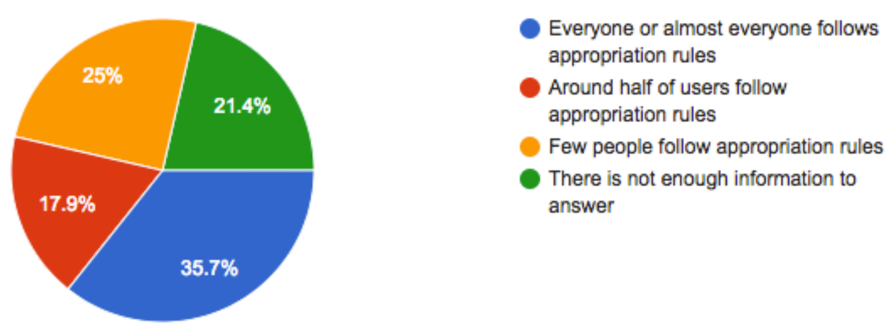
4. Are rules equal for every users?

28 responses



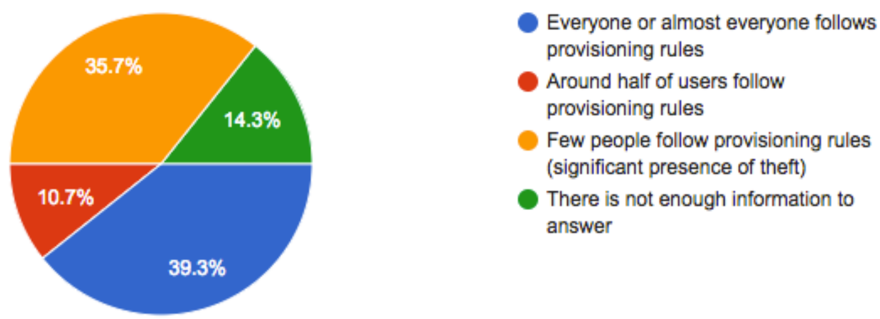
5. Rule compliance: appropriation rules

28 responses



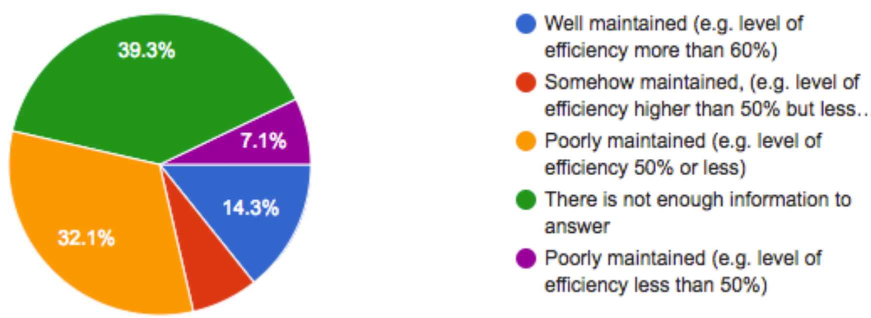
6. Rule compliance: provisioning rules (e.g pay tariffs, canal maintenance work, etc.)

28 responses



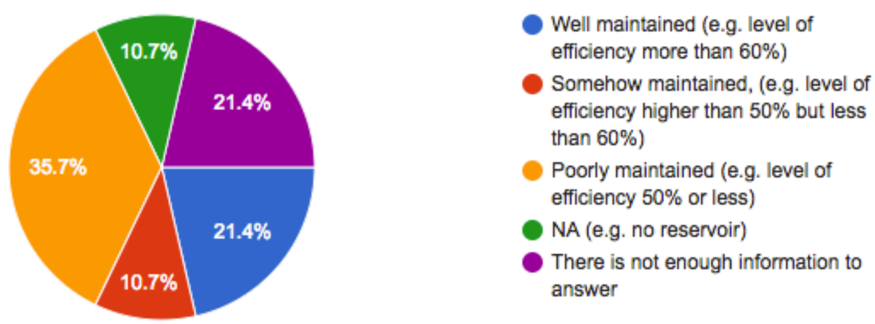
7. Distribution Infrastructure Condition (e.g. Canal)

28 responses



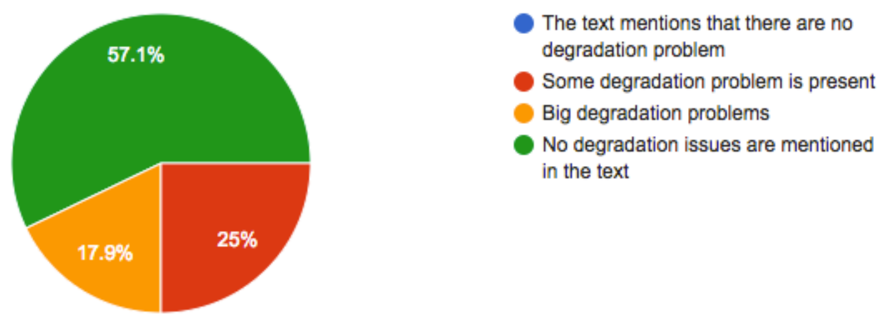
8. Production Infrastructure Condition (e.g. Reservoir)

28 responses



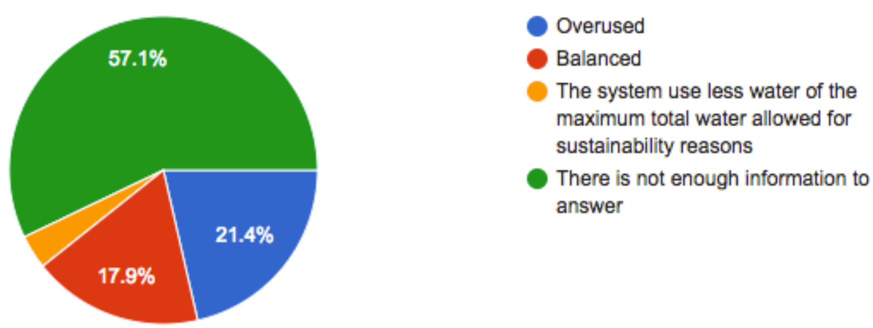
9. Environtmental Degradation (e.g. contamination / salinity, forest reduction)

28 responses



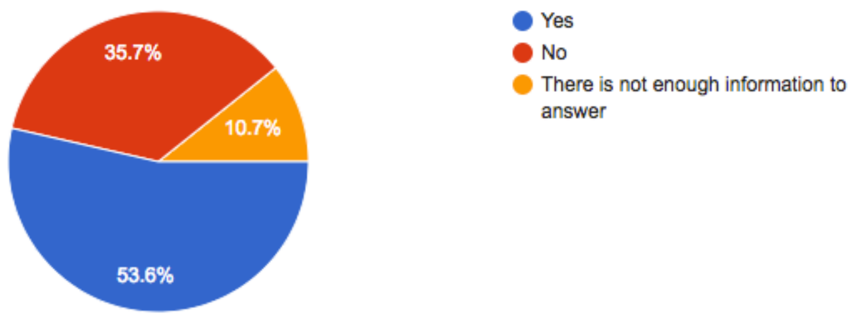
10. Over appropriation of the community as a whole (there must be a minimum of water in the system)

28 responses



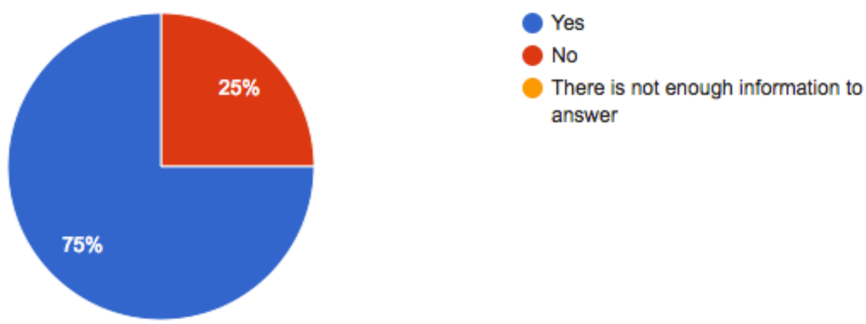
11. Is a group's payoffs being negatively affected by others?

28 responses



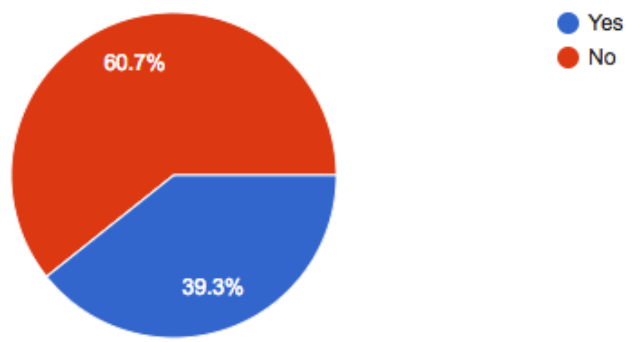
12. Is the system self-sustained? (If there is an external entity -e.g gov, NGO- that gives significant help, then NO)

28 responses



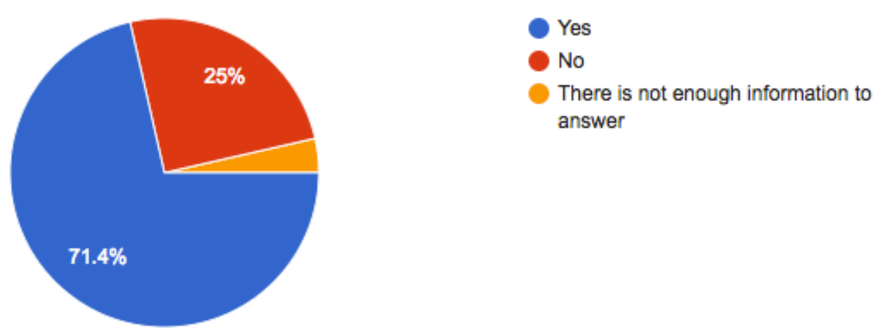
13. Do you think this case is successful ? (Success: No over appropriation, AND no critical conflicts, AND Self-sustained systems, AND poverty is not a problem)

28 responses



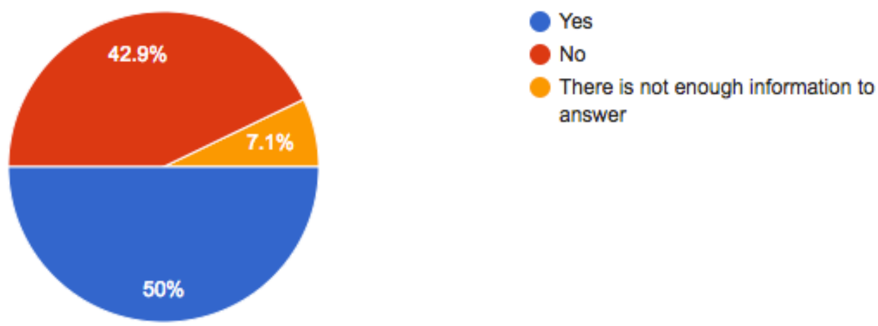
14. Is it clear who are the users of the resource and their rights are recognized?

28 responses



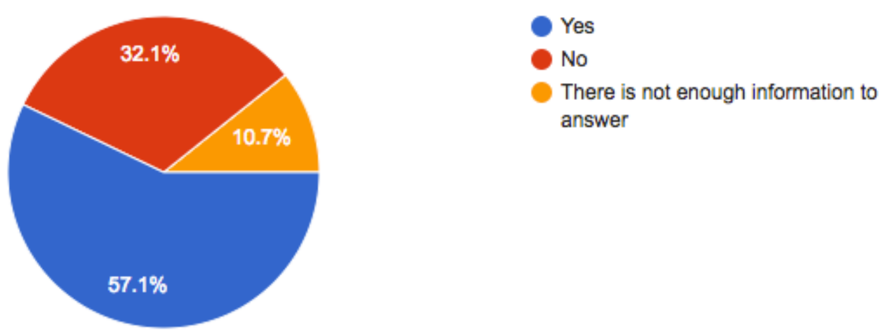
15. Are the borders and water sources that the community can use clearly defined?

28 responses



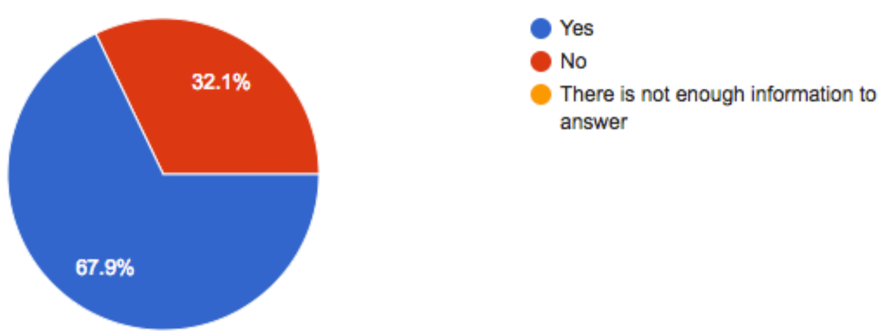
16. Do operational rules (not necessary rules in use) consider a proportional equivalence between benefits and costs?

28 responses



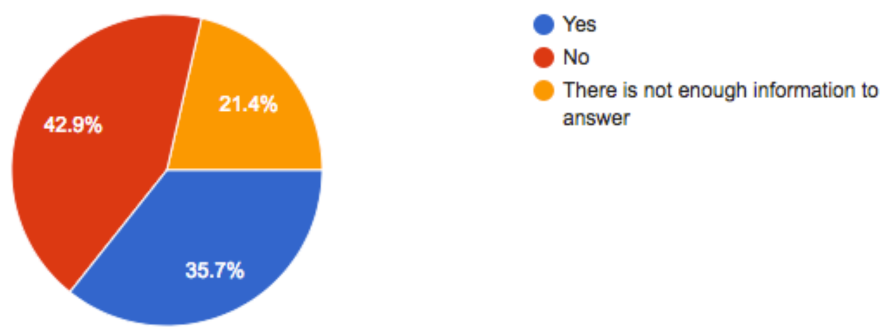
17. Are appropriation rules flexible to fit local conditions (ecology and culture)?

28 responses



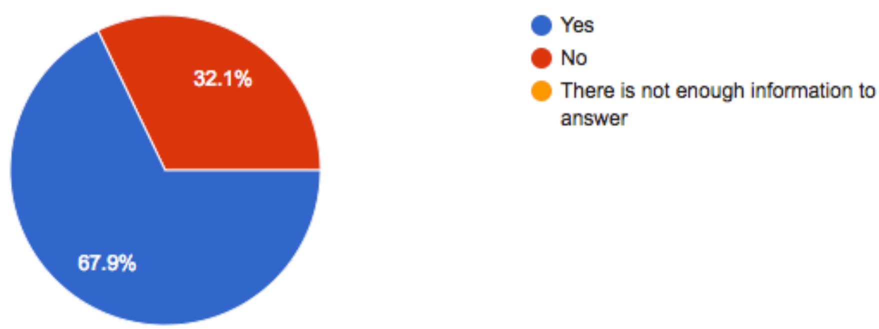
18. Do Appropriators think rules are fair?

28 responses



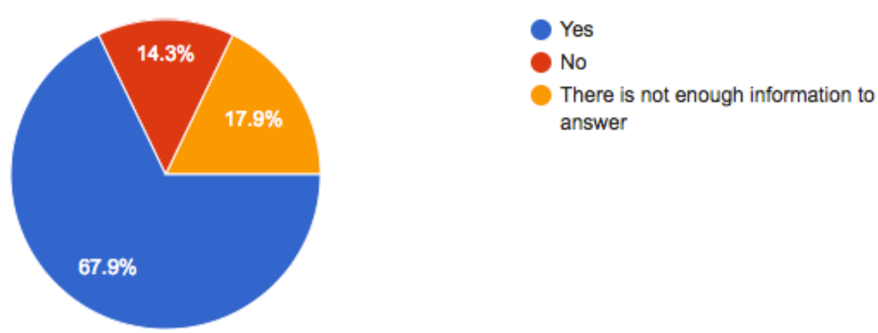
19. Is there a space (physical or not) to express users' needs and concerns to the ones that make decision and these are actually taken into account?

28 responses



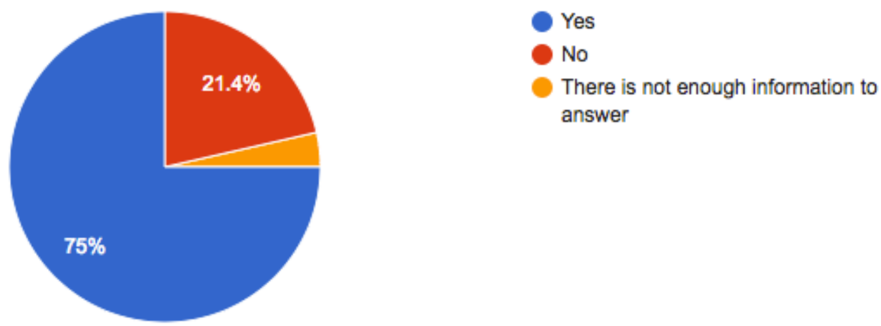
21. Has there been collective action to change rules?

28 responses



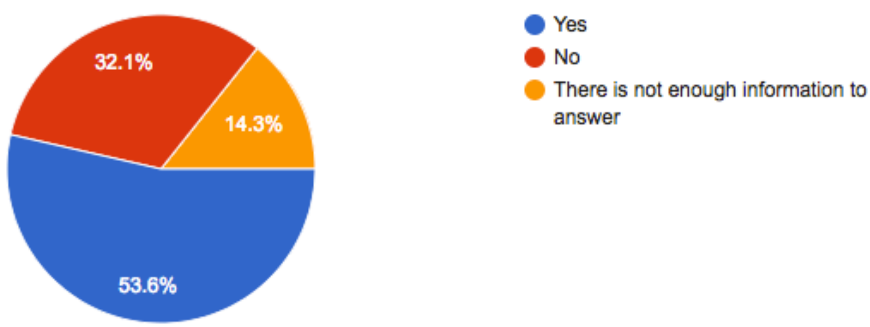
22. Does someone monitor the resource appropriation?

28 responses



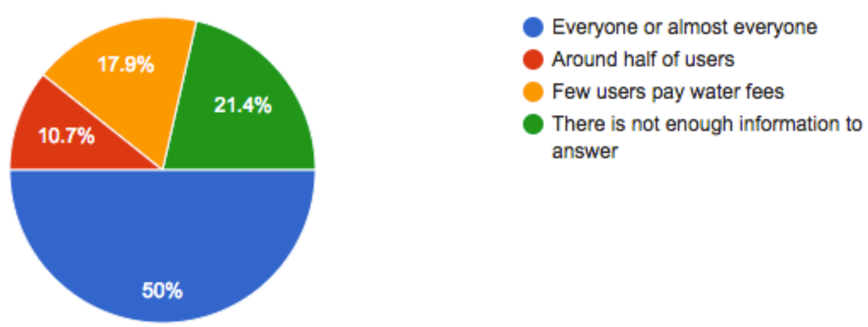
23. Are monitors of water appropriation accountable? Is it well-enforced (users actually believe that they can get caught when getting more of their share)?

28 responses



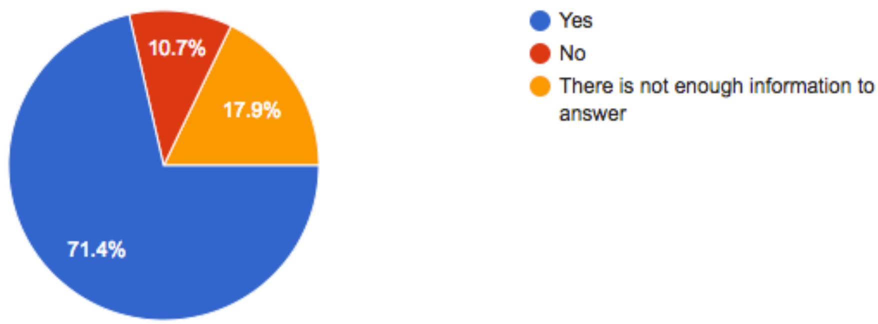
24. Do users pay water fees

28 responses



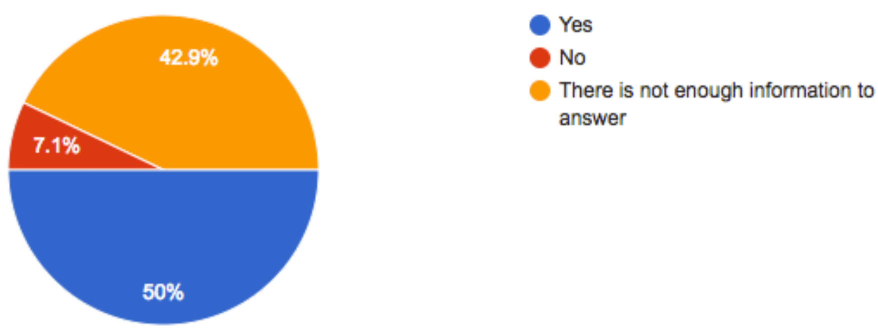
25. Do they keep records of the water level in the river, reservoir or groundwater?

28 responses



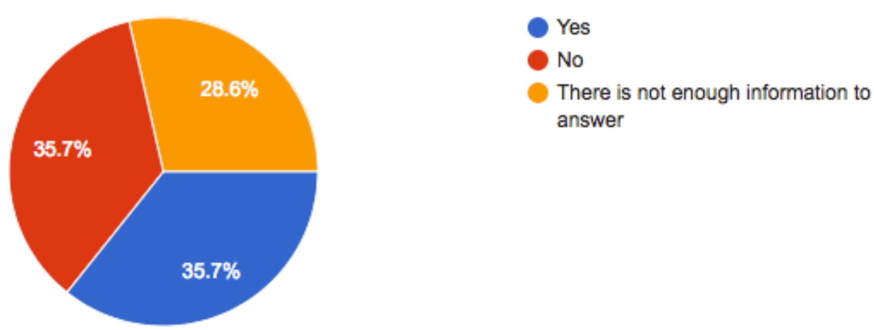
26. Do they register the conditions of the hard human made public infrastructure (canals, reservoir, etc.)?

28 responses



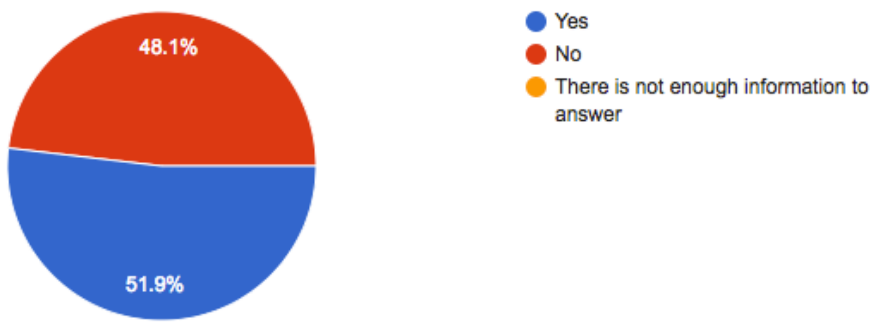
27. Do they have graduated sanctions and this are known by users?

28 responses



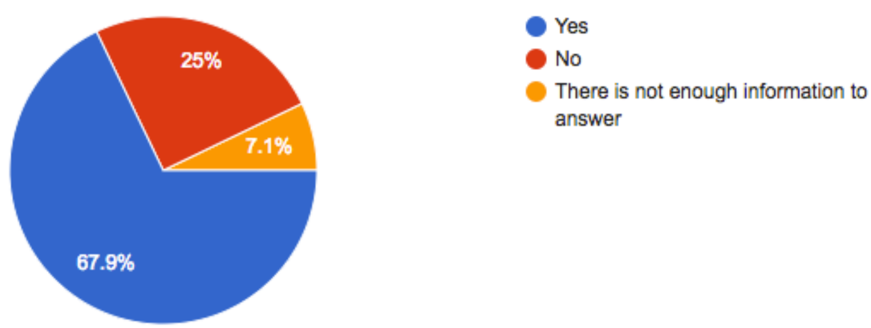
28. can you infer that users believe that they can get caught and be fairly sanctioned if they do not cooperate?

27 responses



29. Is there at least one shared space/area for conflict resolution that it is being used?

28 responses

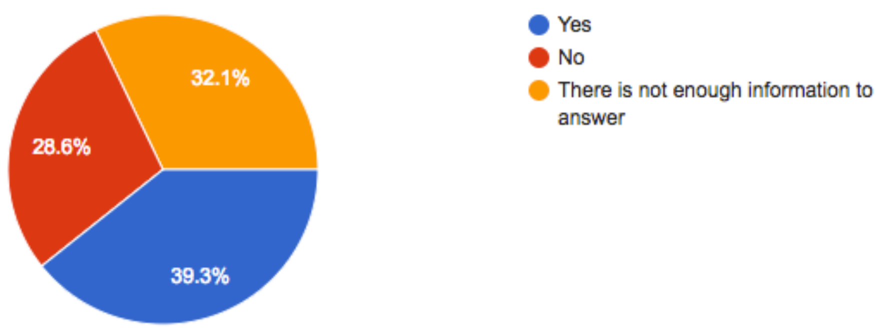


30. Is it true that: Appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities are well organized in multiple layers of nested enterprises and they don't conflict with each other?

28 responses

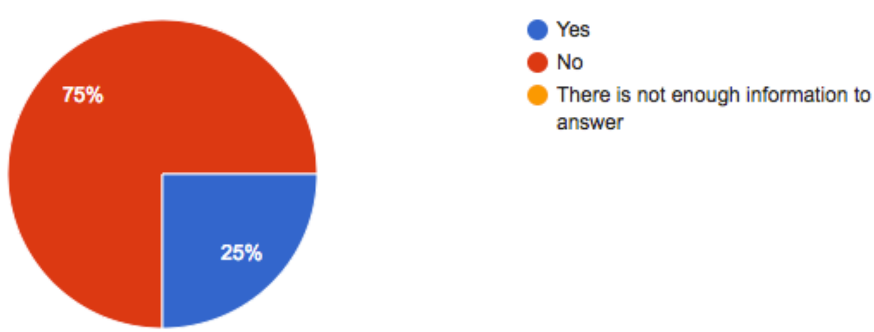
31. Transparency of management. Do users know management details?

28 responses



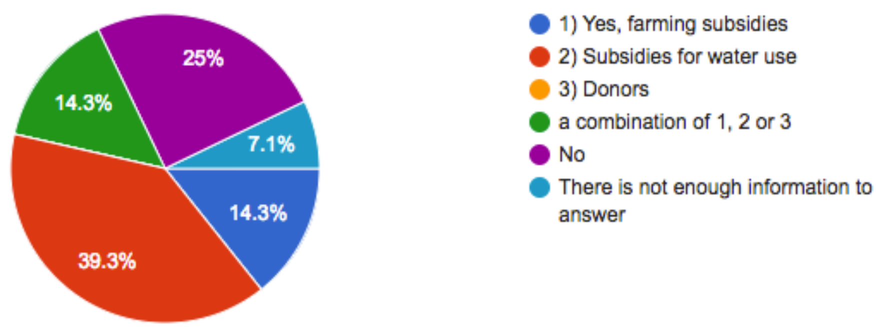
32. Are Non-Governamental Organizations involved?

28 responses



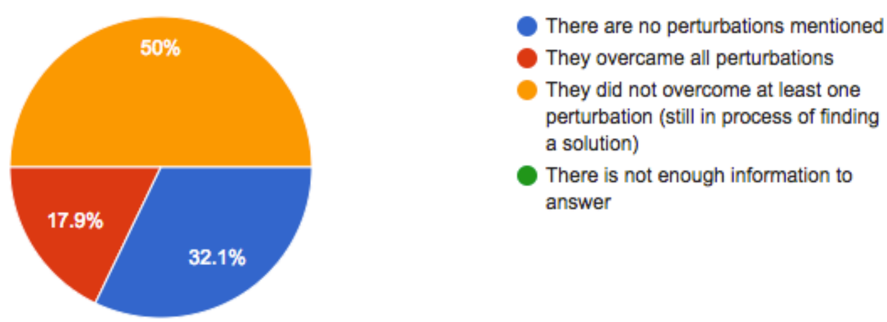
33. Do users have governmental support (e.g. subsidies) or Donors?

28 responses



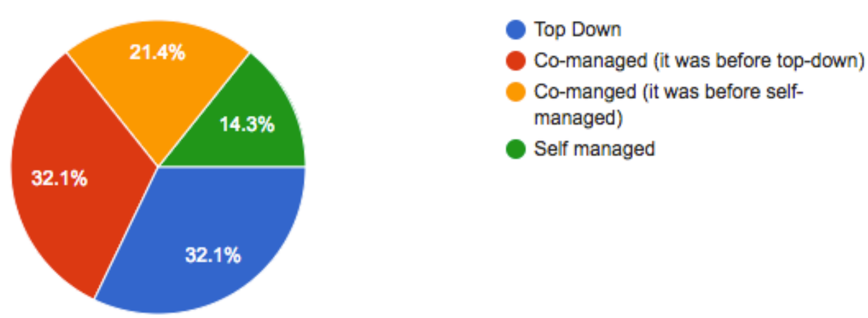
35. If there was a perturbation are they still in the process of adjusting?

28 responses



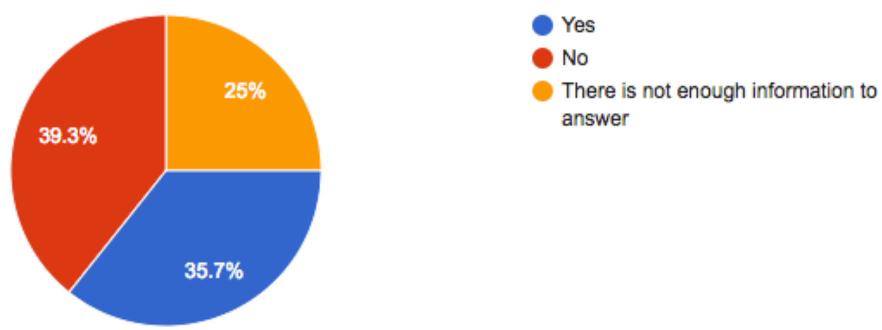
36. Type of governance

28 responses



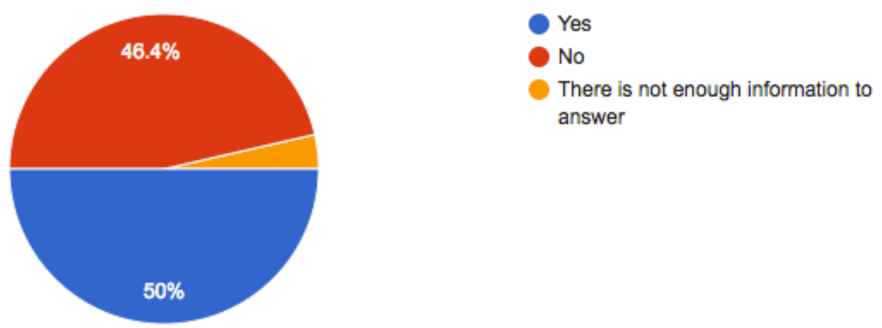
39. Can users see most of other users water appropriation

28 responses



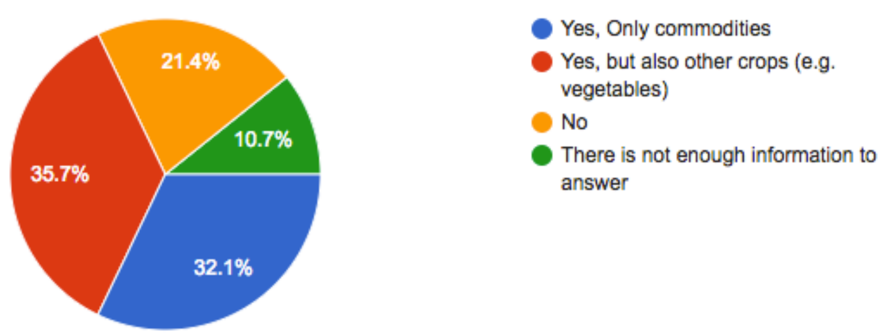
40. Are crops also watered with rain?

28 responses



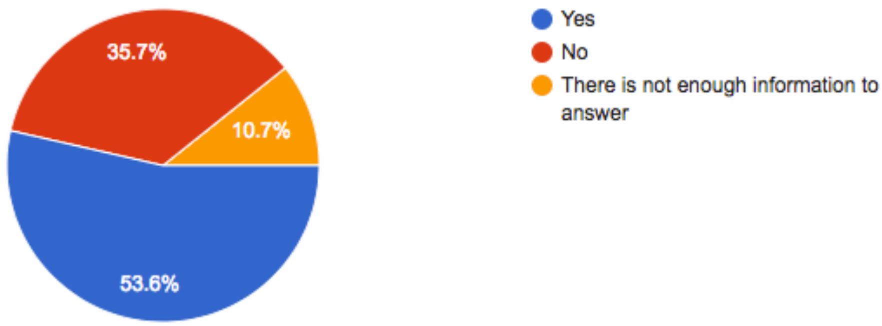
41. Are users growing commodities? (rice, maize, corn, sugar, cotton, grains, Coffee, etc.) – low prices)

28 responses



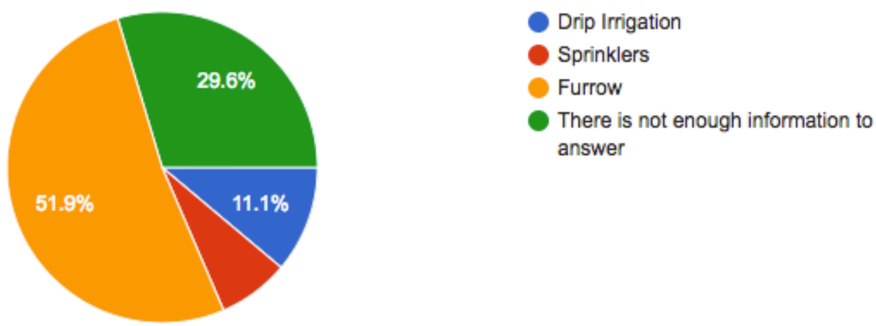
42. Are they growing high water demanding crops? (rice, sugar cane, nuts, corn, cotton, tomato, alfalfa, almond)

28 responses



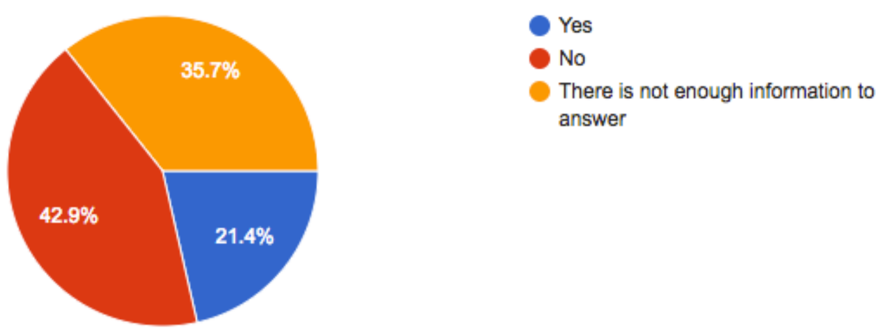
43. Technology to irrigate fields

27 responses



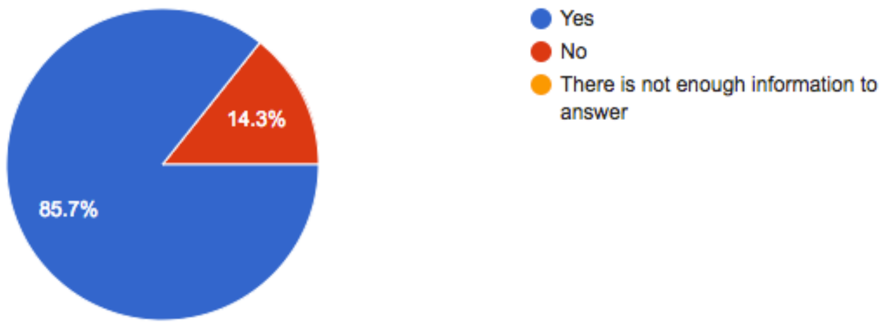
44. Is the human made hard infrastructure very technical and expensive to maintain?

28 responses



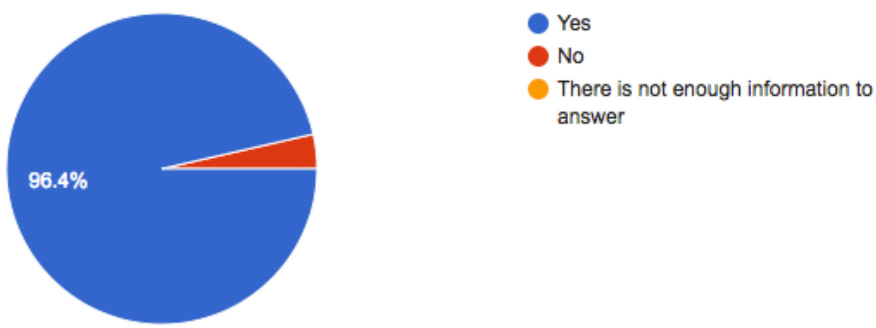
45. Do they store water in a way? (Reservoir, dam, tanks, wells)

28 responses



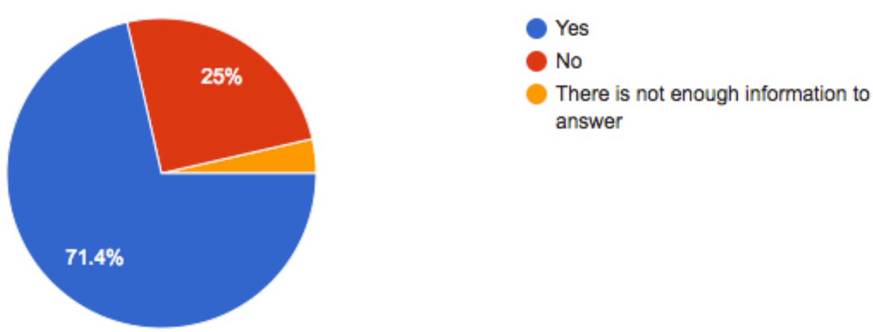
46. Is there a perception of scarcity for most users?

28 responses



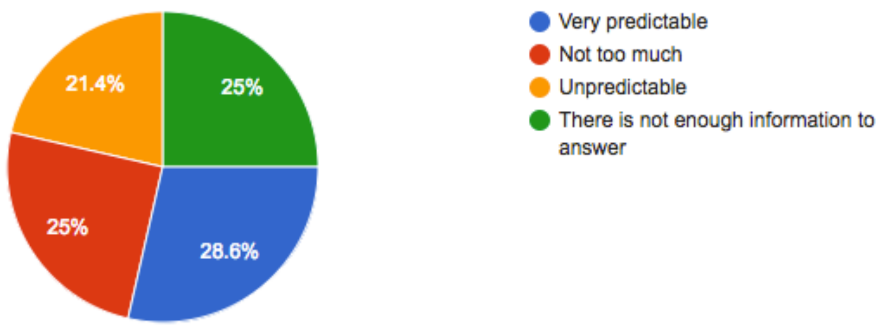
47. Is the system asymmetric because of biophysical characteristics? (Upstream – downstream)

28 responses



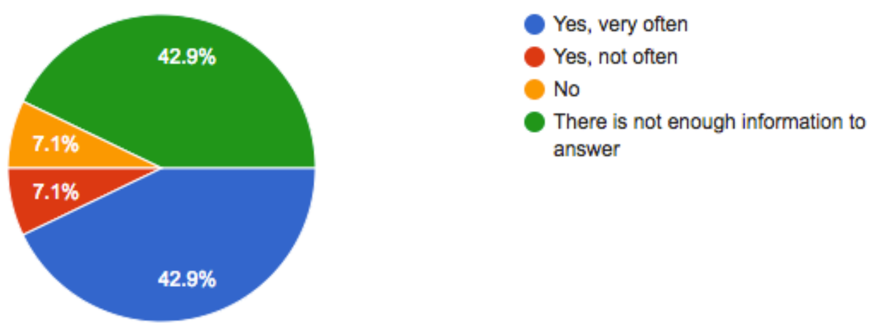
48. Is the weather predictable?

28 responses



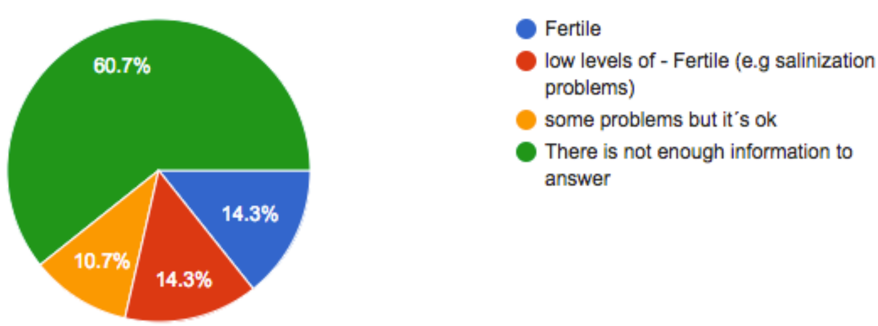
49. Is the system exposed to natural disaster?

28 responses



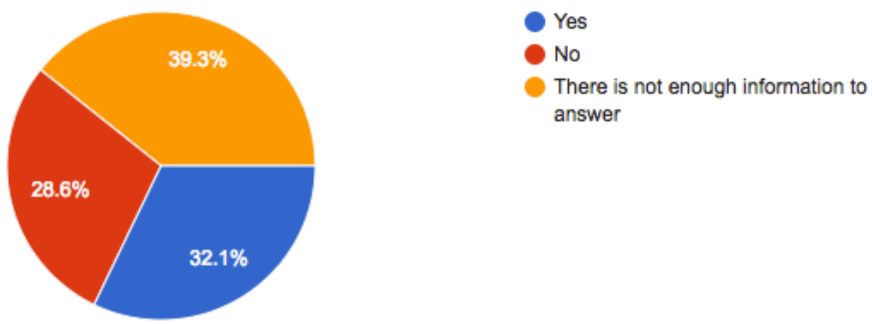
50. Land condition

28 responses



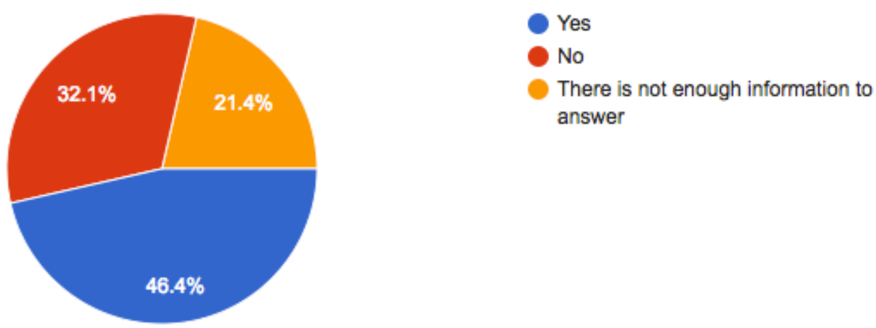
52. Is there trust among users?

28 responses



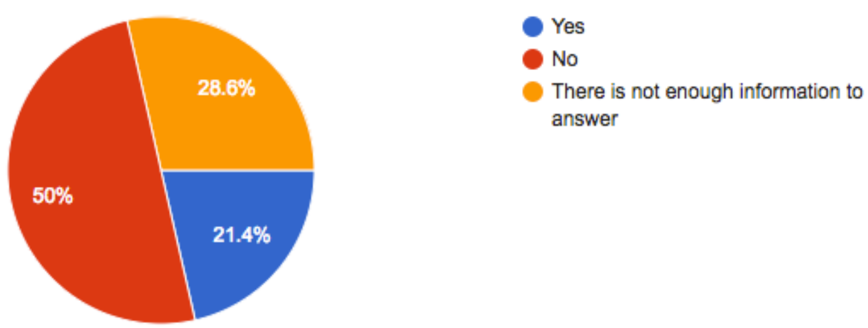
53. Do users trust their leaders?

28 responses



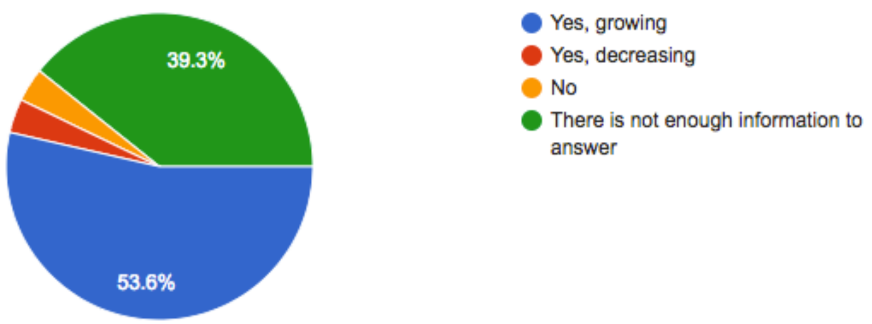
54. Are users homogenous?

28 responses



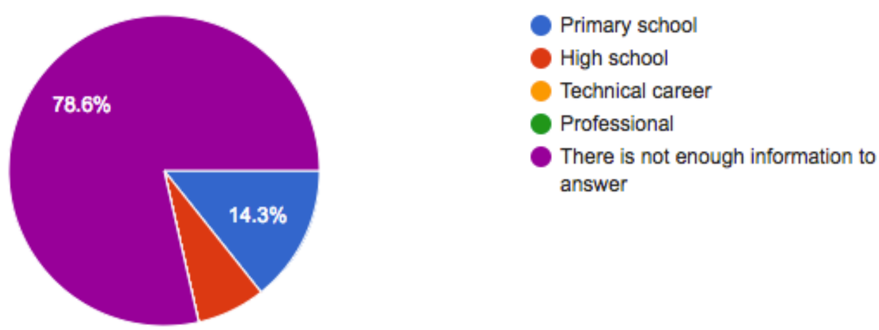
55. Is the number of users changing (significantly)?

28 responses



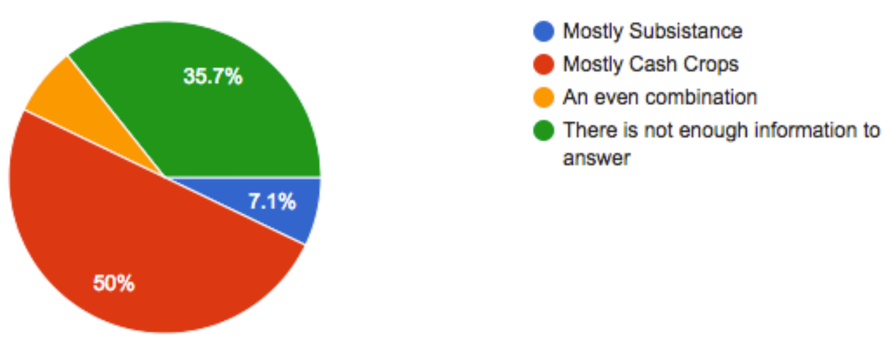
56. Level of education of most of users

28 responses



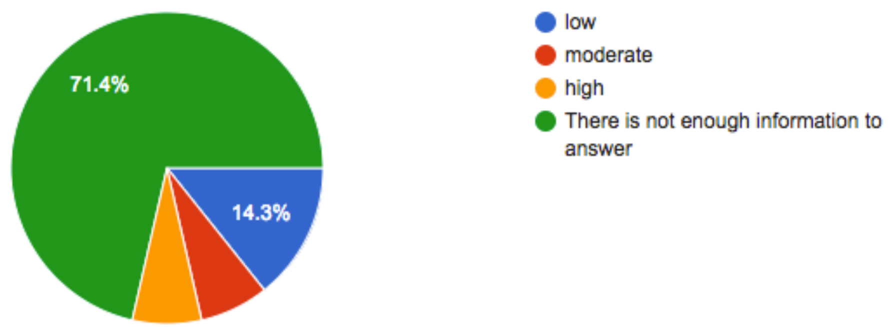
57. Is it mostly subsistance agriculture or cash crops?

28 responses



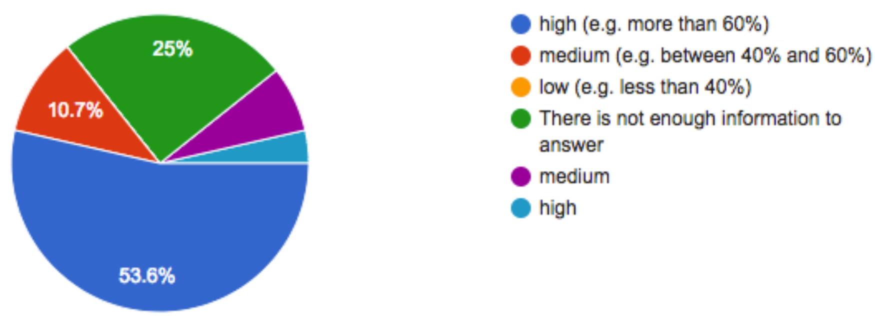
58. User's knowledge of Farming Practices

28 responses



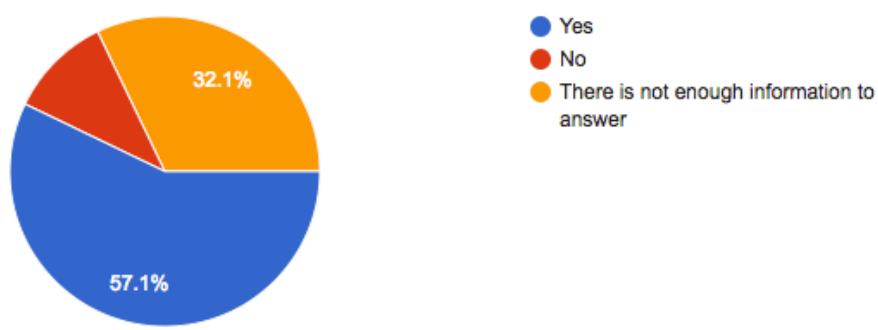
59. Farmers dependence on Agriculture

28 responses



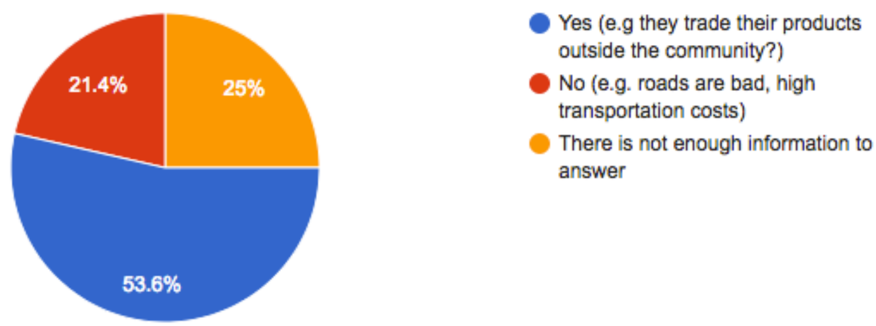
60. Do they have information about the behavior of other users with regards to public infrastructure provision (if users contributed or not)?

28 responses



61. do they have a good level of market integration?

28 responses



APPENDIX E

INTERVIEWS PROTOCOL FOR CHAPTER 4

Interviews Protocol

Actors

How many farmers are there in the basin? How many upstream and downstream the river? for the main crops production and of those of high value added? How are they organized? Are all of them regulated? Has the number of farmers being increasing? What do farmers need to do to have the right to use water of the system?

Actors Roles

Who are the water managers? How is the Irrigation Association constituted? How they take decision? Do they coordinate with other stakeholders? How? What is the role of the local and national authorities for water management?

What role has the Irrigation District / Local Authorities/ National Water Authority / others played in agricultural policy that affects agricultural production? What role have they played in water policies? What role have they played in El Niño related events?

Crop choice

In the last several decades, what has been the primary driver(s) of change in crop production in the basin?

Crop prices and input prices: how they drive decision?

How does this change in El Niño events?

Rules

Can you tell me about Governmental policies about water management and agricultural policies. How the law is implemented?

Can you tell me about the Governmental support for agriculture? Is there special support for El Niño events investments or decisions?

What is the process to change rules?

What policy changes could be made to increase the adoption of innovative and best management practices?

What other changes would need to occur; for instance with agricultural finance or government incentive programs?

What are the most relevant policy changes affecting the type of crop production in the basin over the past few decades?

How does the new water law affect current water management in the basin?

Water Resource and Water Storage

What is the main human made hard infrastructure? Does it help in times of water shortage? Does it help in times of flood events? How is this type of infrastructure affected in El Niño Events? How has it change in the past 10 years? Is the climate changing? Is it affecting water availability or demand?

How do farmers respond to water scarcity, e.g. drought conditions? Do they respond? Are they sensitive to changes in water availability more generally? Who are more sensitive to it?

Have droughts or floods affected your decision-making?

How do water managers decide or not to build/ maintain new human made hard infrastructure? How does this change in el Niño years?

Water Allocation

How water is delivered? How is it treated? How the water allocation is decided? Which is the dynamic for getting water? How are water prices determined?

Irrigation Technique and water use

How is soil quality? How does the irrigation technique affect it?
What irrigation technique do you use for farming?
Can you describe your typical irrigation regiment over the course of the season?
How do you initiate an irrigation event? Is it planned before the season, or do you decide when you want to irrigate and the district responds?
What influences your water use decisions?
Does the irrigation district limit/regulate your water allocation? If so, how?
Does irrigation district pricing/deliveries/policy affect farmers? How?
How do farmers decide the amount of water they apply to their fields? Is there heterogeneity among farmers for these decisions?
How does these changes in El Niño events?

Agricultural Practices

Who would you consider the most innovative farmer in the basin with regard to water conservation practices? What technologies or practices has she/he adopted? Why did he/she make these changes?
How long have you been a farmer?
Have you made changes on your farm? Why? How?
Do you rotate crops? If so, what spurs a rotation, how often do you rotate, and what crops do you rotate into?
What are the labor demands for your farm? Is labor available?
What are the most important issues facing the agricultural industry?
Do El Niño events have changed your decision with respect to farming?

APPENDIX F

DATABASE FOR CHAPTER 4

Table F.1

Resource Users

	Variables	History	Comments
Resource users 1 1 See also population statistics, and other social indicators (1940 - 2015)	**Number of water Users**	The tallanes where the civilization that was settled in Piura when the Spaniards arrived (XVI C). Their organization was not centralized, they lived in clans or family groups. They lived along the Piura river complementing the diversity of crops that they could grow in high places and in the valleys (Huertas 1996)	* In medium and lower Piura there are 75,176 farmers with small parcels averaging 0.65 ha. The main crops in the Medio y Bajo sub-basin are rice, cotton, corn, and beans, all of which have a safe market (GRP. 2008) * There are farmers that have license for water use, and they have priority over those that came later and have not regularized their rights. There is more room (in terms of land and water rights) for agriculture to grow. Many farmers with small parcels (atomization) creates the problem of higher coordination costs for crop growing and water allocation (different timing, higher water loss) * (AACHCP 2008): In Piura (in total) there are 114,127 farmers: 57% less than 3has with 81,376 has (7% of the total). 35% from 3 to 9.90 has (191, 379 has, 16% of the total), and 0.56% of farmers with 719,780 has
	Population in the system		*1.45 million habitants in Piura (the second most densely populated according to Cuanto (1996), today is the third more populated region
	Socioeconomic	Archeologists (Larco, Uhle & Kroeber, 1945; Butters & Castillo, 2008) think that the reason why the Moche society was much wealthier than other societies of the same period was their irrigation capacity	* The Piura basin has high poverty rates, which combine with poor territorial planning, negative impacts from mining activities, deficient road networks, and climate hazards, creates a vicious circle and high obstacles to its deveopment development (GRP, 2007). *(Foncodes, 2007) Piura has a unsatisfied basic needs index of 0.5775, undernutrition rate of 33%, 29% of kids younger than 12 years, women illiterate rate of 14% (the total is 13%, and in rural Piura 23%) a population without electricity of 38%, without dranaige system of 32% and 35% without potable water. According to (Ceprar, 2015): • Weak leadership and social excersize in social organizations • Bourocratric public management, low devepolment efficiency • Inadequate infrastructure management of social and productive services • Inadequate design and technologies in social building. • Polotical interferences in natural resrouce management. • Low family capacities for technification and farming diversification, and well management of natural resources
	Norms/ Social Capital	* Moches: Very hierechical society. Leaders were thought to have divine power (Butter & Castillo, 2008) * Tallanes practiced Mitas, which was a collective action labor effort for public and private construction in the time of the Incas (Huertas, 1996)	*To be eligible for irrigation, farmers must be members of the non-governmental and non-profit National Irrigation Association, Junta Nacional de Usuarios de los Distritos de Riego del Perú (JNUDRP), which is subdivided by valleys. For the Bajo y Medio Alto Piura, there are three irrigation associations: Medio y Bajo Piura, Sechura, and Huancabamba. • There are strong and representative organizations: peasant comunities, peasant monitoring, users organizations, farmers organizations, enterprenerus organizations, and women organizations. • National and international market organization. •Research center, academic capacitation and multidisciplinary training: Higher technological institutes, Universities • Public and private institutions, local governments, that support with ressources the sustainable development of the region * Farmers work alone. They do not trust in each other to associate for that (in Alto Piura) * When they grow rice, it helps to capture water when El Niño happens. And rice is not sensitive to floods. * Farmers from the Chira Valley would like to have bigger seasons. At the begging they claim that the water was theirs, but now they have accepted that they need to share it with the Piura Valley. * McEntire and Fuller (1980): Peru's social fabric is very weak, because the government has discouraged organization due to their fear that any type of association involves terrorits activity. Therefore, a weak social fabric made it very difficult for victims to respond quickly and recover from the triggering agents
	Conflic among users	In the 70s there was a land reform, and owners had to give their land to their emplyees that knew few about farming. This generated many problems of trust from framers to their leaders (Huertas, 1996)	Conflicts in the basin are between farmers and the mining and energy sectors (IRAGER 2013)

Table F.2

(A) Population in Piura According to Census of the indicated Years

Year (Census)	Total Population	Rate between Censuses (Annual Average)
1940	432,844	--
1961	692,414	2.3
1972	888,006	2.3
1981	1,155,682	3
1993	1,409,262	1.7
2005	1,679,899	1.5
2007	1,725,488	1.3

Source: Instituto Nacional de Estadística e Informática (INEI) – Censos Nacionales de Población y Vivienda

(B) Human Development Index (HDI) and its components. Piura Region in the National Ranking 2007

Population		HDI		Life expectancy at birth		Literacy		Level of Education		Family Income per Capita	
Habitants	Ranking	HDI	Ranking	Years	Ranking	%	Ranking	%	Ranking	USD/month	Ranking
1676315	2	0,59788	13	71.74	16	90.8	15	82.4	17	90	11

Source: Instituto Nacional de Estadística e Informática (INEI) – Encuesta Nacional de Hogares (ENAHO)

Table F.3

Public Infrastructure Providers

	Variables	Comments
Public Infrastructure Providers	**Governmental**	*Main PIP: -Ministery of Agricutlure, Ministery of Health. - Development Entities: Regional Government of Piura, Proyecto Especial Chira Piura (Since 2003 the cental government started the transference of the Hidraulic Proyects. El Proyecto Especial Chira Piura was transfered to the Regional Gobernment of Piura) , Proyecto Binacional Catamayo – Chira - Municipality Provincial de Huancabamba * Rule Making Entities: - Autoridad Autonoma de Cuenca Hidrografica Chira Piura - Administración técnica (National Water Authoritty) de los Distritos de Riego San Lorenzo, Chira, Alto-Piura, Medio y Bajo Piura - Dirección de Salud – Dirección Ejecutiva de Salud Ambiental. -Service Entities: - Entidad Prestadora de Servicios Gracu SA - Juntas administradoras de servicios de saneamiento * Since 1992: Autoridad Autónoma de Cuenca Hidragráfica Chira – Piura (AACHCHP): Chira, Piura and the high basin of Huancabamba (Decreto Supremo N020 – 92 – AG) (AACHCP 2008) * in the 80s, Private and Public institutions developed different initiatives that ended up in “Declaración de Piura” For Natural Resources Conservation in 1988.
	Users Associations	* Users Association of the Irrigation District San Lorenzo, Chira, Alto Piura, Medio – Bajo Piura y Users Association of the Irrigation District Sechura; * Users Association of the Irrigation District of the Andean Valley of Huancabamba *Users Association: irrigation comissions and canal comissions
	Non Governmental Organizacion	*In 1994 Irager (association for information with respect to water uses) was created

Table F.5

Table F.4
Public Infrastructure

Variables	History	Comments
Hard PI Performance	Moches: Build big canal systems. large network of irrigation canals and reservoirs (around 816 km)	*In Poechos Reservoir (the biggest reservoir of Peru), there is regulated water and non regulated (when it cannot be captured). Poecho, captures less than 50% of its initial capacity because of sediments. * Downstream (medio y bajo piura) of the Rio Piura there is nont natural water. Only in abundance periods. * They have to leave 5m3 to the sea (for Chira) and 1m3 (for Piura) for the ecologic balance, but they cannot fulfill this claim every month. THey compensate later when water is abundant. * The irrigation system maintenance is in charge of the Water User association. For San Lorenzo and Bajo Piura the drainage system is of 166.6 Km. that is not in good condition for insufficient maintenance activities. *If the want to make an open system of dranaige, it implies that they should use a lot of land for the dranage, the maintenance roads, and others. This implies loss in agricultural land * There are non-working dranaige, full of vegetation and trash. Its maintenance requires high cost machinery which are not covered by the user association *Water Loss in the Canals: Derivation (10 - 15%), 5% in small canals, and 15% in Bajo y Medio Piura globally (ALA 2004) * techincal defects became apparent in some of the mitigation works because of corruption (Mineo, 1998) * There is sea intrusion throuh the drainage system whe El Niño comes
Soft PI Performance		* Sectorial Management is prioritized over multisectorial water management. * There are not concrete disaster prevention plans. Thi is the duty of the Regional Government. * Water User Association are fragile, but they do give some maintenance for prevention * In the 2017 The Early Warning System did not work.
Equity		The drenage system is artificial, and does not arrive to the sea. There is a lake full of salt, and the sea level is higher now.
Anticipation Capacity	None. The Moches though that it was punishment from the gods.	* Six months before, the International Decade for Natural Disaster Reduction's Consultative Council confirmed in the summer of 1997 that el Ninho was happening. Even though Fujimory undertook a massive prevention campaing, prevention was not enough. In Piura, a proposed drain, which would have reduced the volume of water in the Piura River by diverting it to the Ocean, never materialized * (AACHCP, 2008) In december 2002, with the help of GTZ they intalled The system of early warning [Sistema de Alerta Temprana (SIAT)] – That gets hidrometereological information of the basin , process and elaborates the forecast with 48 hours of anticipation of extraordinary events. *Limited information about grounwater level and condition (PARLCDS) In 2015 a strong Niño was anticipated for 2016, but it was moderated (it actually came by surprise on 2017). The central government allocated 300 millions for prevention to Piura. The Regional Government did not use the total amount allocated for prevention (ojo publico, 2017)
Reservoir, Dams, Canals and Drainage	*The Mochica society was agriculturally based, with a well-developed and large network of irrigation canals and reservoirs (around 816 km) to divert and store river water to supply their crops in desert areas. * Excesive water was diverted to natural or human made lakes. The canals were destroyed by natural dissasters in the 30s *The Tallanes settled in Piura and built canals to grow mainly corn, cotton, native fruits like lucuma.	*The Reservoir helps to amortiguate in flooding events. * El niño caused damaged and brought sediments to the reservoir. *Total Drainage is 55.27km for the Chira River. They are considerating building a reservoir for Alto Piura, but they want users to pay for it and they do not have enough resources * Hard Public Infrastructure was built for Chira, Medio y Bajo Piura and San Lorenzo. Poechos Reservoir was built in 1976 with a capacity of 885 mmc. Until 2012 there are 467mmc of sediments (52% of its total capacity). *Alto Piura does not have hidraulic infrastructure for its regulation * Derivation Canal Daniel Escobar of 54km long and 70 m3/s. It is derivated to the Piura River. The Reservoir helps to amortiguate in flooding events. * Irrigation Infrastructure was destroyed with el niño of 1982 and in 1998. Dranaige, dams, derivation canals, defense infrastructure.
Market Integration	In pre-hispanic times there were roads that connected the valley with important centers in the highlands, even with the Inca civilizations. Roads in the coast throuhg the ocean and terrestrial adquired important relevance in different periods (G. Lumbreras, 1979; J. Richardson, 1987).	(Irager 2016) *El Niño 1997 – 1998 It was more intense than 1982, but shorter. Big impact in rural and urban infrastructure (bridges and sanitary) Transportation infrastructure was also destroyed (air and land).

Resource

	Variables	Comments
Resource	**River**	*The Piura Valley is located in the North Coast of Peru close to the equatorial line. *It is semi-arid with low precipitation ang high temperatures. *The Piura River starts at the intersection of the River Bigote and River Canchaque *The River is 280 kilometers long, and the basin surface is 12,216 km2. The basin is divided in two irrigation systems, "Alto Piura" on its right margin, and "Medio y Bajo Piura" on its left margin.I will focus my analysis on the Medio y Bajo Piura sub-basin, because this area is more exposed to El Niño flood events than the Alto Piura sub-basin. Water from the Piura River is almost completely used before reaching Medio y Bajo Piura, but the sub-basin receives water from the Poechos Dam (from Chira River) through the "Daniel Escobar" canal that was built in the 1970s (GRP, ANA & GTZ; 2009). The Piura River's flow is normally low, but in El Niño events the river grows to a point that it becomes dangerous. For example, in the station of the river that is called "Sanchez Cerro," river flow in a normal year is no more than 140m3/s at its highest, but in 1983 it increased to 3,200m3/s, and in 1998 to almost 4,500m3/s, damaging irrigation and road infrastructure (GRP et al., 2009). *Alto Piura, has higher precipitation levels (C. Collin Delavaud, 1984). It is very variable–With periods of strong droughts-, Though, since colonial times agriculture was possible (J. Helguero, 1984; L. Huertas, 1987). * Water for the Medio y Bajo Piura (and that goes through Poechos) comes from the Binational Basin Catamayo Chira (16700km2). 7085 km2 (57,60%) are in Ecuador que equivale al 57,60%., in Peru is called Rio Chira * In the high area there are big extensios of dry forests * There are metalic resources as gold, silve, among others <u>Zones:</u> Lower Zone : sea to 50 msl, flat slope (which is problematic when flood events happen) Midum Zone: 50 - 35 msl0, curvy slopes High Zone: 350 - 3650 msl with shapr topography, rivers of steep slopes and V sahpe valleys
	Weather	* Normally you have 10 years normal and then have extreme droughts, that is the normal behavior of Piura River. There was a drough in 94 - 95 * Desertification has always been a problem in the Valley because of its high temperature, low precipitation, high evotranspiration, combined with the fact that it is arid and flat, next to the sea, and highlands area are considerated fragile (Guevara & Molina 2009)
	water and land	Every water have salt (even rain), but more when it moves through the soil, and even more when it has been stored . In raining seasons, (Jan - April) water that goes through Piura has only 500 ppm (1/2 k of salt by m3) but in dry seasons (Sep – Nov) the same water that comes from Poechos has 3 times salt than in rainning seaons: 100 ppm (1,5k of salt by m3) *Because the slope is flat, and the irrigation uses flooding techniques (and even more than needed), the land closer to the coast have salinization problems. * In 2004 there was a drought. * Bajo Piura has the worst indicator of salinizations, followed by Bajo Chira, San Lorenzo Valley and then, Medio Piura. 30% of the land (30,000.00 ha has this problem) (Gobierno Regional Piura,Estudio ZEE. 2010). * With respect to the loss of land because of water erosion this is worse in Alto Piura (but this affects el bajo Piura in flood events) * Poor agriculture practices also affect the soil quality
	Forest	* Deforestation and soil erosion in particular play a significant role in this discourse, along with suggestions of increased salinization from irrigation and agricultural intensification (Chew 2001, 2005; Diamond 2005, p. 487; Ponting 2007). * This is a big concern since long time ago. In 1975 Sabogal-Wiessel wrote about how deforestation and desertification since 1920s had been a problem (for energy and agriculture) * The Piura Basin has 1'222,840 has of forest (56.5 % of the total area of Piura)
	Systems dynamic predictability	* Accordin to the COLPEX PROJECT 80% of water occurs in Mar – April. During the year there is 100 MMC in extremely dry years and more than 3,000 MMC in humid years (average 1120 MMC - year). Maximum avenues are in the Puente Sánchez Cerro station during FEN 1983: Piura River reached 3,200 m3/seg and in 1998 4,500 m3/ seg * Weather variability is new, FEN has always existed. It's the combination of both what is affecting the region now

Table F.6

Private Infrastructure

	Variables	Comments
Private Infrastructure	**Land Characteristics (soil)**	*Agrarian Reform in the 1970s *Soil Slinization specially in the lower basin *In alto Piura in 15 years the salinization levels have been duplicated *From 1997: Problems such as the high salinity of coastal soilds nowadays affect 40% of the arable lans in this region. * 50% to 60% of this region's surface (Alto Piura) can be considered as deteriorated. * Both on the Coast and in the Sierra. desertification has basically been caused by human factor through farming, stockbreeding, forest and mining activities that have led to salinity, water, soil and genetic eriosion as well as water an air pollution . Activities such as deforestatin poor water management, inapropraiate use of soil, overgrazing and forest fires together with demographic pressure and low living standards are the determining factors for the different desertification processes in Piura such as soil erosion, genetic erosion, salinity, fragmentation of the vegetation covering he gronud, destruction of habitats, reudction of fauna and extinction of species. All this brings aobut food shortages and insecurity lower living standards (poerty), alterations in the water balance and the food cycle as well as microclimatic changes that lead to further arid conditions * (Gobierno regional Piura, 2010), in Piura Region there are 716,584.99 Ha in desertification process, of which 543, 872.37 Ha are due to deforestation and 172,712.62 Ha to salinization, hidric erosion and poor drainage.
	Irrigation Technology	Mainly Fooding for rice (farmers even use more of what the crop needs), infiltration problems, salinization and land degradation
	Human Infrastructure	Poor farming and irrigation practices. Low management capacities (See education Levels Statistics)

Table F.7

Link 1: Resource Users and Resource

	Variables	History	Comments
Link 1 (Resource Users and Resource) **(See also statistics of agricultural land, production and productivity)**	**Productivity**	Moches: *Their main agricultural products were corn, peanuts, cotton, fruits, and, in the highland areas, different types of potatoes (Velásquez, 2015), which they were able to trade with other societies (Butters & Castillo, 2008). * According to Sabogal-Wiesse 1975 they grew up 5% of the total area for agriculture. * Monocropping was introduced by Spanish conquerors (Guevara & Molina., 2009)	*There are 2 main farming seasons: Big (Jan – March) when water is abbundant and the small season. The crops that have priority are: rice, cotton (yield has decreased and the demand is controlled by few companies) * El niño is affecting already some productivity, like the Mango that now there is overproduction and underproduction (specially when it is cold). Algarrobo is been affected by plagues * There is a small but growing group of farmers who are starting to grow mango, peppers, grapes, and other fruits (GRP et al., 2009).
	Resource importance	Water was central to their civilization (Velásquez, 2015)	*Agriculture is an important productive activity in the basin, involving about one-third of the population (INEI, 2012). 48,534 ha are used for agriculture, of which 84% is irrigated (AACHCP, 2008) *In the lower basin the main crop, is rice with 31,014 has, followed by yellow corn with 12, 313 has other type of corn with 8967 has *Huertas: Agriculture consumes 90% of available water. They grow more of what it is programmed, which affects prices. Users do not pay water tariff as they should
	Appropriation Characteristics	NA	*Before, farmers used to wait for big avenues of the river to flood deserted land in the lower valley. Only then they could grow crops there. They also used to store water in natural or artificial lakes. Now this is not practiced because 1) Communal canals to deviate water are not used any more 2) They work for money and not collectively (Sabogal-WIesse 1975) Irrigation eficiency is 35% for the lower valley (floding) before, they used to use less water because they used to pump water and thus they had to pay energy costs. * In 2016 farmers used more than needed for growing rice, in Jan 2017 they declared the valley under drought and in feb 2017 strong rains hit the valley. The named it "Nino Coster" because it was regional, not prevented and outside the cycle.

Table F.8

Main Crops Production in Piura (1950 – 2015)

	Production (T)					
Year	**Cotton**	**Rice**	**Onion**	**Sweet Potato**	**Corn**	**Haba (bean)**
1950	22,170	13,468	--	--	--	--
1951	19,233	14,832	--	4,225	--	--
1952	33,728	27,888	--	4,225	3,005	--
1953	35,104	24,511	--	4,225	4,956	--
1954	61,766	30,171	--	1,710	4,920	--
1955	56,938	32,640	--	1,795	5,375	--
1956	71,249	30,194	--	1,795	5,565	--
1957	67,370	25,495	--	2,420	7,780	--
1958	89,751	25,487	--	3,600	6,686	--
1959	83,360	46,072	--	6,020	6,725	--
1960	103,909	58,670	--	6,020	7,200	--
1961	97,594	54,481	--	3,150	6,605	--
1962	123,374	69,775	360	3,500	8,749	351
1963	128,269	62,510	391	3,430	8,984	374
1964	125,800	46,920	2,425	4,450	11,250	467
1965	99,750	23,520	8,100	9,580	15,700	161
1966	131,250	56,760	20,934	11,895	23,200	136
1967	86,505	72,485	26,661	14,026	22,788	171
1968	93,520	53,132	13,148	8,655	22,268	149
1969	74,400	87,458	7,620	10,288	27,600	206
1970	86,700	104,500	8,659	8,885	32,190	469
1971	76,791	116,070	7,370	8,073	33,681	419
1972	68,190	54,050	7,273	7,269	33,619	320
1973	82,736	69,764	7,902	3,648	21,840	273
1974	100,750	63,220	12,457	5,149	15,428	311
1975	71,064	74,336	4,770	6,262	40,165	312
1976	63,607	82,264	11,942	5,752	58,149	291
1977	52,744	87,282	3,020	5,084	49,038	175
1978	62,071	93,920	5,080	4,655	17,271	188
1979	73,939	99,089	3,078	6,396	24,219	207
1980	74,288	109,749	2,880	2,253	27,776	110
1981	61,758	128,375	631	1,293	23,586	112
1982	50,446	174,131	6,815	1,172	12,946	180
1983	4	76,082	--	542	16,240	144
1984	50,482	195,679	1,249	1,605	42,422	220
1985	80,859	117,899	849	1,283	20,168	196
1986	92,531	126,238	2,205	1,744	28,237	219
1987	36,800	178,440	3,919	2,098	56,324	195
1988	74,555	224,505	10,640	1,403	30,680	174
1989	103,000	132,842	9,233	1,754	60,827	165
1990	86,564	167,406	4,306	2,129	54,867	138
1991	47,506	115,150	2,893	532	38,328	103
1992	25,191	162,062	5,478	2,715	91,661	80
1993	27,460	187,826	4,791	5,081	52,911	99
1994	26,384	247,267	3,800	1,624	56,144	--
1995	59,829	132,181	2,850	3,694	28,652	--
1996	90,181	120,023	5,013	3,378	29,132	--
1997	27,380	241,299	666	3,386	30,928	285
1998	716	205,504	6,195	4,265	51,003	177
1999	27,908	272,156	1,840	3,815	50,741	139
2000	41,236	235,401	4,104	3,485	54,942	167
2001	23,730	259,897	2,648	1,222	53,597	112
2002	10,060	341,616	2,215	5,886	64,512	144
2003	14,168	368,598	1,592	5,933	58,822	150
2004	28,936	252,053	1,944	3,008	64,768	256
2005	31,294	426,374	4,151	11,781	51,413	342
2006	35,162	359,254	4,404	32,159	76,324	644
2007	40,369	402,128	10,506	22,830	63,777	449
2008	21,974	529,837	6,058	17,820	61,381	450
2009	9,057	520,671	9,432	26,846	67,136	507
2010	5,032	499,845	14,955	28,376	76,139	409
2011	11,946	383,315	15,606	21,934	82,081	451
2012	5,482	607,847	6,155	13,277	64,881	463
2013	4,784	550,431	5,759	16,165	76,848	542
2014	9,951	356,507	6,810	9,607	54,390	321
2015	4,577	503,241	8,196	15,257	65,010	447

Source: Ministry of Agriculture

Table F.9

Main Crops Production in hectares in Piura (1950 – 2015)

	Production (Ha)					
Year	**Cotton**	**Rice**	**Onion**	**Sweet Potato**	**Corn**	**Haba (bean)**
1950	14,128	3,844	--	--	--	--
1951	20,615	3,395	--	650	--	--
1952	44,535	5,965	--	650	1,711	--
1953	54,179	6,228	--	650	2,949	--
1954	49,235	6,989	--	300	2,990	--
1955	49,210	7,400	--	335	3,220	--
1956	49,752	7,319	--	335	3,082	--
1957	56,979	6,189	--	540	3,864	--
1958	61,338	5,973	--	600	3,841	--
1959	56,524	10,595	--	800	3,843	--
1960	65,318	12,063	--	800	3,400	--
1961	54,377	11,721	--	450	3,220	--
1962	61,200	13,351	30	500	4,738	270
1963	63,620	12,980	33	530	4,655	283
1964	74,000	8,500	200	650	7,500	670
1965	75,000	4,900	900	1,400	10,000	360
1966	75,000	11,000	2,270	1,560	11,600	230
1967	73,000	13,300	2,690	1,690	11,900	305
1968	56,000	9,015	1,170	1,060	7,900	285
1969	62,000	14,950	955	1,220	11,500	360
1970	51,000	19,000	905	1,300	11,100	550
1971	53,700	21,900	705	1,285	14,730	570
1972	45,460	11,500	785	1,105	15,055	425
1973	51,710	16,300	850	535	8,000	360
1974	65,000	14,500	1,335	760	5,610	405
1975	57,310	16,160	505	1,030	14,550	370
1976	43,270	18,080	1,115	960	20,220	340
1977	45,352	18,000	305	823	17,766	215
1978	40,516	17,170	465	708	5,757	250
1979	45,250	17,275	283	772	8,649	288
1980	47,257	19,356	320	440	10,338	163
1981	39,716	23,906	61	235	7,723	165
1982	29,885	29,766	592	186	4,211	301
1983	29	17,490	--	130	4,958	320
1984	19,491	35,417	113	315	12,756	363
1985	51,927	21,132	75	272	6,167	390
1986	63,590	19,632	210	305	9,079	296
1987	37,730	33,069	340	397	16,981	300
1988	41,687	33,579	532	270	8,778	290
1989	60,700	21,664	798	303	18,145	280
1990	54,449	24,475	289	259	14,873	275
1991	41,769	18,232	203	101	10,494	195
1992	28,978	25,353	384	586	27,390	160
1993	19,956	27,693	396	899	16,120	180
1994	15,159	39,285	282	221	16,862	--
1995	32,670	21,435	201	293	8,381	--
1996	41,277	17,447	350	393	8,260	--
1997	25,110	30,409	66	419	9,434	199
1998	624	30,944	445	1,089	15,754	205
1999	13,842	48,438	130	485	14,411	128
2000	24,774	30,952	229	570	15,600	152
2001	14,858	34,797	171	249	14,891	126
2002	10,333	45,024	147	585	17,885	152
2003	7,688	45,424	81	538	14,576	168
2004	15,510	32,543	115	312	15,866	254
2005	17,790	47,243	167	912	13,368	323
2006	14,184	42,199	288	1,357	20,673	622
2007	16,271	43,369	369	1,086	17,303	429
2008	9,132	56,822	295	929	17,866	531
2009	3,395	56,778	394	1,247	16,764	550
2010	2,396	55,358	627	1,271	19,747	425
2011	5,959	44,175	718	1,096	18,901	544
2012	6,603	65,374	274	772	16,906	604
2013	1,284	58,702	267	925	18,961	660
2014	3,586	41,284	284	825	14,052	402
2015	2,316	57,559	332	1,046	16,543	562

Source: Ministry of Agriculture

Table F.10

Yields of Main Crops produced in Piura (1950 – 2015)

	Yield (Kg/Ha)					
Year	**Cotton**	**Rice**	**Onion**	**Sweet Potato**	**Corn**	**Haba (bean)**
1950	1,569	3,504	--	--	--	--
1951	933	4,369	--	6,500	--	--
1952	757	4,675	--	6,500	1,756	--
1953	648	3,936	--	6,500	1,681	--
1954	1,255	4,317	--	5,700	1,645	--
1955	1,157	4,411	--	5,358	1,669	--
1956	1,432	4,125	--	5,358	1,806	--
1957	1,182	4,119	--	4,481	2,013	--
1958	1,463	4,267	--	6,000	1,741	--
1959	1,475	4,348	--	7,525	1,750	--
1960	1,591	4,864	--	7,525	2,118	--
1961	1,795	4,648	--	7,000	2,051	--
1962	2,016	5,226	12,000	7,000	1,847	1,300
1963	2,016	4,816	11,848	6,472	1,930	1,322
1964	1,700	5,520	12,125	6,846	1,500	697
1965	1,330	4,800	9,000	6,843	1,570	447
1966	1,750	5,160	9,222	7,625	2,000	591
1967	1,185	5,450	9,911	8,299	1,915	561
1968	1,670	5,894	11,238	8,165	2,819	523
1969	1,200	5,850	7,979	8,433	2,400	572
1970	1,700	5,500	9,568	6,835	2,900	853
1971	1,430	5,300	10,454	6,282	2,287	735
1972	1,500	4,700	9,265	6,578	2,233	753
1973	1,600	4,280	9,296	6,819	2,730	758
1974	1,550	4,360	9,331	6,775	2,750	768
1975	1,240	4,600	9,446	6,080	2,760	843
1976	1,470	4,550	10,710	5,992	2,876	856
1977	1,163	4,849	9,902	6,177	2,760	814
1978	1,532	5,470	10,925	6,575	3,000	752
1979	1,634	5,736	10,876	8,285	2,800	719
1980	1,572	5,670	9,000	5,120	2,687	675
1981	1,555	5,370	10,344	5,502	3,054	679
1982	1,688	5,850	11,512	6,301	3,074	598
1983	138	4,350	--	4,169	3,276	450
1984	2,590	5,525	11,053	5,095	3,326	606
1985	1,557	5,579	11,320	4,717	3,270	503
1986	1,455	6,430	10,500	5,718	3,110	740
1987	975	5,396	11,526	5,285	3,317	650
1988	1,788	6,686	20,000	5,196	3,495	600
1989	1,697	6,132	11,570	5,789	3,352	589
1990	1,590	6,840	14,900	8,220	3,689	502
1991	1,137	6,316	14,251	5,267	3,652	528
1992	869	6,392	14,266	4,633	3,347	500
1993	1,376	6,782	12,098	5,652	3,282	550
1994	1,740	6,294	13,475	7,348	3,330	--
1995	1,831	6,167	14,179	12,608	3,419	--
1996	2,185	6,879	14,323	8,595	3,527	--
1997	1,090	7,935	10,091	8,081	3,278	1,432
1998	1,147	6,641	13,921	3,916	3,238	863
1999	2,016	5,619	14,154	7,866	3,521	1,086
2000	1,664	7,605	17,921	6,114	3,522	1,099
2001	1,597	7,469	15,485	4,908	3,599	892
2002	974	7,587	15,068	10,062	3,607	947
2003	1,843	8,115	19,654	11,028	4,036	893
2004	1,866	7,745	16,904	9,641	4,082	1,008
2005	1,759	9,025	24,856	12,918	3,846	1,059
2006	2,479	8,513	15,292	23,699	3,692	1,035
2007	2,481	9,272	28,472	21,022	3,686	1,047
2008	2,406	9,325	20,536	19,182	3,436	847
2009	2,668	9,170	23,939	21,528	4,005	922
2010	2,100	9,029	23,852	22,326	3,856	962
2011	2,005	8,677	21,735	20,013	4,343	829
2012	830	9,298	22,464	17,198	3,838	767
2013	3,726	9,377	21,569	17,476	4,053	821
2014	2,775	8,635	23,979	11,645	3,871	799
2015	1,976	8,743	24,687	14,586	3,930	795

Source: Ministry of Agriculture

Table F.11

Link 2: Resource Users and Public Infrastructure Providers

	Variables	Comments
Link 2 (RU - PIP)	**Collective choice rules**	*Farmers elect association leaders every 3 years (partiicpation rate is ver low. The associations are divided into users' commissions, which are subdivided into canal committees.
	Users perception are considerated	If users do not attend the assemblies, they have to pay a fee. There are delegates for each groups. They were not going before, but now they are. Delegates are chosen by farmers, and they represent them in the meetings. For every 200 farmers, there is 1 delegate. Conflicts are mediated through delegates, with the help of the municipality *For the meeting (assemblies) to be valid, there have to be 10% of active members For elections at least 50%.

Table F.12

Link 3: Public Infrastructure Providers and Public Infrastructure

	Variables	History	Comments
Link 3 (PIP - PI)	**Self-organization activities**		*The main role of the users water association is to operate and maintain the public irrigation infrastructure (dams and canals), distribute water, collect and manage fees for water use, determine water tariffs, cut water services to non-
	Non governmental support		(Irager 2016) Piura changed its governance and was opened to international cooperation (for FEN disaster recontruction and to fulfill the binational agreement with Ecuador
	Investment Activities	Ports, Houses from Conquers. It was the first Spanish city in America. People settled in Piura because of the Rio Piura, and the proximity to the port (Pacific Ocean)	*In Latinamerica, Peru is one of the countries that has invested the most to expand irrigated land. In the last 40 years Peru has invested aproximatedlly 25 to 35 thousand USD per hectare. However, this governmental effort hasn't been profitable and there were any prevention to flood events (DE AACHCP, 2008) *Prevention, Mitigation and FEN 1997/1998 Management. (National Comision of Emergency, Presidential, funded by PNUD (Irager 2016): -Environmental policies (from 2011) - Conflict management (2005) -2011 regional strategy to climate change 2011: environmental policies got official 2011: regional technical group for coastal marines areas and wetlands 2014: Risk analysis in the context of climate change included.
	Control Concentration	Moche: Their political system was centralized and very hierarchical, with a cast of religious and military leaders dominating farmers (Bouden, 1996).	To approve water tariff proposed by water users association. According to the Law of 2015 to formalize their right users have to pay (before it was free) The Regional Water Authority (ALA) supervise the service quality that the users association provides Minor Operator: Users Association (But the State is the owner) Mayor Operators: Proyecto Especial Chira Poechoes (PECHP- IN charged of the regional government) There is a Water Committee formed by: The users association, ALA, PECHP, Farmers from different commissions and agricultural ministry) They gather every Tuesday. According to the size of the irrigated land, farming intentions, permanent and transitory crops, water available in the reservoir, water allocation is decided. The Water supply has a probability of 75% of persistence. They have to fulfill first the domestic demand, and then agriculture is supplied. There is always scarcity, otherwise agricultural land would grow in size. *For the 2016 - 2017 ni;o, the central government gave an important amount of money for prevention programas. This is just for emergencies, because it is the region that should invest on a regular basis (but they do not do it) * The concentration of political power may have limited the capacity of local leaders and emergency managers to undertake the steps they felt were necessary to prevent calamity

Table F.13

Link 4: Public Infrastructure and Resource

	Variables	Comments
Link 4 (PI - R)	**Storage Characteristics**	Poechos. 50% of its initial capacity of storage.
	Distribution	*Computarized irrigated comissions. They give water to those that have paid in advane. There have been a sensibilization probam, and they are responding well (farmers) *Now only 10% do not pay, before it was 70%. It is Chira the ones that do not pay. *FEN preparation is not every year, and the water association fdo not participate

Table F.14

Link 5: Public Infrastructure and Appropriation Dynamic

	Variables	Comments
Link 5 (PI - Appropriation)	Monitoring	In el alto Piura, there are water thief problems (divert water with pipes or block with stones) There are monitors, but farmers are very angry. The last drought was in 2011. In 2017 they though that a drought was coming, but a sudden El Niño occurred.
	Sanctioning	Sanctions to industries, like the Energy industry, are not enfforced.
	Operational Rules	*Water Availability is link with the economic capacity of the system When farmers deliver their farming intentions generally they ask for less water of what they really want. At the time of allocating water, farmers ask for more water. When water is scarce, everyone participates (Farmers), but when it is abundant nobody assist to the meetings organized by the mayor operator. *The maintenance of the minor infrastructure is underprovisioned. In the lower they are better organized, but not everyone pay tariffs. The law says that if they don't pay they should not get water, but this is not enforced. There are no monitoring mechanisms.

Table F.15

Link 6: Resource Users and Public Infrastructure

	Variables	History	Comments
Link 6 (RU - PI)	Provisioning rules	Before 1991, farmers used to collectively organized and work together to clean the infrastructure. When farmers were asked to pay a water tariff instead, this was lost	Farmers are used to avoid water tariff payments. They argue that their farming profit is not good, which is true. Then, if they increase the water tariff, they make a strike in the highways, and water is very cheap. Though, this year more users have paid. They get more embarrassed when named in a non-payment list. Water tariffs should pay for the whole maintenance. The cost is 20 millions and they collect only 4 on 2015, 6 millions in 2016. They want to improve the condition of the reservoir, but only the study on who to do this has taken them 14 years. The cost is of 200 millions dollars. Then, it is no profitable * Farmers are disconformed with public infrastructure * Users Association have maintained their canals in the lower basin (some of them), but in Chira there is more disorganization. The world bank was involved before, they were paying for the maintenance, but now they are gone. *See water tariff statistics

Table F.16

Link 7: External Forces on Resource

	Variables	History	1982/1983	1997/1998	2017	
					Before	After (planned)
Link 7 (External Forces on Resource)	**Spread from other system or to other system (interconecteness)**	Moche: The civilization was settled in all the Peruvian north coast. When the series of El Niño events happened all the settlements (not only those in Piura) were affected		*Deforestation in the high area of the Basin affects downstream • Lost of crop fields due to floods • In the lower basin the napa freatica increased • Anchovy was reduced to half, and other fish species for human consumption were reduce to 1/4	International Connection: Sediments come from Ecuador, but for them that is not a big issues.	
	Environmental Events	• Weather temperatures are increasing and are more variable. This affect crops productivity. For lemon for example, this is a good effect, but for Mango, Algarrobo, Rice, Corn, this can be negative. • Low water quality • Sea water vulnerable to changes in temperature • Forest expossed to deforestation, droughts, and fires. • River with low slope, vulnerable to floods and big avenues from the highlands. • Hard infrastructure is vulnerable to to the FEN • Lack of drainage in some cities make hem vulnerable to floods • dessertification • Vulnerabilidad de los suelos de la parte baja por elevación del nivel freático.	Extreme Drought in 82 and Flood in 83 * sea temperatures increased to 7.7º C in 1983 and to 8º C in 1998.	*The rain cumulates and in short periods of time rains for all the season (flood) (110 mm, 4000 vs 800) * Recent agents included flooding and mud-slides due to an excessive amount of rainfall, sea surges emanating from strong ocean currents and winds, and drought owing to excessive heat and the lack of precipitation in some areas. The first two of these agents were maingly prevalent in the north, the thrid aling the coast, and the fourth exclusive to the south. * The ocean temperatures were not only higher than those previously recorded, but increased at a faster pace as well (Wind, 1998a)*In 1998, the losses were valued at more than US$100 million (CTAR, 1998). *Rainfall in a 1983 event was even higher but because of the higher, deforestation rate the damage was greater in 1998. *In Piura the economic lost was around 17 millions de USD for crop lost	*the rain cumulates and in short periods of tim eit rains for all the season (flood). *The Piura basin still has high poverty rates, which combine with poor territorial planning, negative impacts from mining activities, deficient road networks, and climate hazards, to create a vicious circle and high obstacles to development (GRP, 2007).	It is estimated that and increase of 2°C in the maximun temperature and 20% in the variability of precipitation 2050,can cause a loss of 6% of the potential GDP in the 2030 and in 2050 more than 20%. If global public policies to stabilized climatic variables are applied the damage can be reduced to one thirdr (CERPLAN 2016). In Peru, the main effects of climate change (increase of the global temperature) are the ones related to 1) glaciar reduction, 2) increase in frequency and intensity of el niño and 3) rise of sea levels

Table F.17

Piura: Monthly Comparative Mass Flow of the Piura and Chira Rivers, 1982 - 83 and 1997 – 98

River	Month	Normal	1982 - 83	1997 - 98
Piura	December	63.3	81.9	288.3
	January	177.1	324.4	1893
	February	306.1	1176.4	2965.6
	March	544.1	2244.6	4443.7
	Cumulative Total	***1090.6***	***3827.3***	***9590.6***
Chira	December	194	112.1	602.2
	January	397	1969.9	2438.8
	February	756	919.7	2088
	March	665	3070.1	2204.3
	Cumulative Total	***2012***	***6071.8***	***7333.3***

Source: Executive Direction of the Special Project Chira - Piura

Table F.18

Link 7: External Forces on Public Infrastructure

	Variables	History	1997/1998	2017	
				Before	After (planned)
Link 7 (External Forces on Public Infrastructure)	**Environmental Events**	Normally there are accute droughts and then floods. Since the reservoir was built, the dorughts were controlled, at lower part of the valey, but not floods, and not in the high part of the valley.	Physical damages, losses in the economy and reconstruction expenses were calculated to be near 1 billion USD	Storage capacity has reduced.There are vulnerable points that can be destroyed.	There is in general an economic vulnerability: low productivity, low technology, comerzalization, management and planning. Transportation roads, bridges, drainage, etc. are defficient. * low private investment * low trust * high risk of el NIño (no attractive for private investment)

Table F.19

Link 8: External forces on Resource Users

	Variables	History	1997 - 1998	2017
Link 8 (External forces on Resource Users)	Population Change	The first Spanish city in America was next to the Chira River. After 2 years, due to malaria problems they moved to Alto Piura. After a Mega Niño in 1571 the population moved to the port of Paita. When the hacendados (big landlords) built big irrigation infrastructure, the population from the highlands moved to work in agriculture. In Sechura, in 1728 a FEN washed the city, and the population had to move again. In the last 25 years of the XVI century, many catastrophes has occurred in Piura. Even Zaña was completely destroyed by an intense flood, followed by droughts, diseases	*The severe precipitation and mud-slides left behind an incredible amout of death and devastation. * 374 people lost their lives, aother 412 were injured, and close to 600,000 were affected by the disaster (PREDESS,1998). * over 114,000 hectares of cultivable land were flooded (Vallejos-Munhoz, 1998). *homes, schools, bidges were destroyed. This disrupted the distribution of food that was being harvested. * The fishing sector was impoacted too Credit was limited to small farmers	80 deaths, 111,000 damnified, more than 10,600 houses collapsed, more than 1000 education institutions, 380 heath buildings, 847 km of roads destroyed, 1909 of highways destroyed, among others until march 2017, 600km of irrigation canals destroyed, 8600 ha lost. Total damaged in the country: 3,100 US dollars
	Interconnecteness, Diseases	Moches: They were able to trade with other societies (Butters & Castillo, 2008).	Mudsildes , Plagues	There are conflicts between farmers and energy companies The Binational agreement with Ecuador, provides preferences to the Peruvian water demand because it is greater than Ecuatorian;s demand

Source: Instituto Nacional de Defensa Civil – (INDECI) – Instituto Geofísico del Perú – (IGP)

Table F.20

Piura: Number of Natural Events, Houses Affected, Destroyed, Number of Deaths, Damnified, and Ha Affected (1999 - 2010)

Natural Phenomenon	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Natural Phenomena	18	10	26	46	138	212	191	156	271	221	98	120
Houses Affected	1,612	159	3,812	3,044	369	5,810	5,441	4,185	1,790	41,785	1,137	1,055
Houses Destroyed	179	48	1,339	84	165	178	187	241	243	6,038	42	223
Number of Deaths	-	5	7	7	9	1	-	1	3	7	-	4
Number of Damnified	4,889	1,130	17,105	15,027	2,189	124,576	129,059	57,980	21,635	166,547	44,236	4,658
Farming Hectares Affected	2,200	260	785	7,238	7	88,314	280	16,726	-	6,546	-	7

Table F.21

Link 8:External forces on public infrastructure providers

	Variables	1997 - 1998	2017	
			Before	After (planned)
Link 8 (External forces on public infrastructure providers)	**Network Structure**	2,227 USD lost in Peru Agriculture lost: 613 millions USD	*Mayors are in charge of FEN prevention invesment, but they are more worried in re-election and thus invest in more visible projects. THen, when an emergency comes, the central government invest. This last time, few mayor executed the allocated money in prevention * On the other hand, decentralization missed the proper transfer of knowledge and resources.	Social Vulnerability: • Health fragility due to poor infrastructure, and medical technicians. • Low education levels with poor soft and hord education infrastructure. • Lack of basic needs • High poverty rates (higher than national average) * High migration from the highlands *Increase in unemployment • Weak institutions, with poor management, planification and basin monitoring * Lack of leading capacity • Poor farmers organizations that disencourage modernization

APPENDIX G

IRB EXCEMPTION FOR CHAPTER 4

Knowledge Enterprise Development

EXEMPTION GRANTED

John Anderies
Human Evolution and Social Change, School of (SHESC)
480/965-6518
Marty.Anderies@asu.edu

Dear John Anderies:

On 7/1/2016 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	Comparing Robustness and Fragilities in Coupled Infrastructure Systems: El Niño in the irrigation system of the Mochica Society and in the Current Piura Basin, Peru.
Investigator:	John Anderies
IRB ID:	STUDY00004531
Funding:	Name: National Science Foundation (NSF), Grant Office ID: DNS0253, Funding Source ID: GEO-1115054
Grant Title:	DNS0253;
Grant ID:	DNS0253;
Documents Reviewed:	• Translation Certification Form Piura.pdf, Category: Recruitment Materials; • Translation Certification Form Piura.pdf, Category: Consent Form; • CONSENT LETTER _ Piura.pdf, Category: Consent Form; • Consent Letter_PIURA_ BACKTRANSLATION PP.pdf, Category: Consent Form; • Recruitment-script Piura.pdf, Category: Recruitment Materials; • Anderies Rubinos HRP-503a-PROTOCOL.docx, Category: IRB Protocol; • Recruitment-script Piura_BACKTRANSLATION PP.doc.pdf, Category: Recruitment Materials; • Interviews Protocol Piura.pdf, Category: Measures

	(Survey questions/Interview questions /interview guides/focus group questions); • Recruitment-script Piura_SPANISH.pdf, Category: Recruitment Materials; • Consent letter - Piura SPANISH.pdf, Category: Consent Form; • full_proposal_nb.pdf, Category: Sponsor Attachment;

The IRB determined that the protocol is considered exempt pursuant to Federal Regulations 45CFR46 (2) Tests, surveys, interviews, or observation on 7/1/2016.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc: Cathy Rubinos
Cathy Rubinos
John Anderies
Joshua Abbott

APPENDIX H

CALIBRATION FOR CHAPTER 5

State Variables	Initial Condition	Reference
E_t = Performance of the physical engineered construction in time t	0.85	Leonidas (2009). The model starts in 1980 when the current irrigation infrastructure was built.
S_i^C =Fraction of cooperators in group i.	0.26	Leonidas (2009), ANA (2008)

Parameter	Value	Source
Q^S= Naturally produced water	4,000 in normal years, 17,000 in el Nino events, and 18,000 for future scenarios when specified.	Leonidas (2009)average of normal water availability, real data from el NINO, and projected for potential future events.
N_1=Number of users upstream	9,170	ANA (2009) Number of has to assume average farmer = 1ha
N_2=Number of users downstream	31,516	ANA (2009) Number of has to assume average farmer = 1ha
l= Length of the canal for group	30	Proyecto Especial Chira-Piura (2016).
a= Coefficient of water loss	0.01	ANA (2008)
Θ= Depreciation	0.2	Proyecto Especial Chira-Piura (2016). Responds to a higher rate of depreciation because of the sediments that the river brings from upstream deforestation.
q= monetary value of the additional output generated by the first unit of irrigation water	1.45 S/. per m3 (unless other value is specified)	Rice production function from (Jalote et al., 2007), adapted for yield and price from statistics of MINAGRI (2017)
r= determines how the marginal value changes as the amount of appropriated water changes	0.000075 S/. per m9	Rice production function from (Jalote et al., 2007)
c= Marginal cost of water appropriation	0.46 S/. per m3	Rice production function from (Jalote et al., 2007), adapted for cost in Piura from DGIA (2008)
δ=The cost of monitoring	100 S/.	ANA (2009)
γ = Sanction	1750 S/.	D. Ley 17752 Ley general de Agua (2010) 50% of 1UIT. UIT = 3,500 in 2008 retrieved from and SUNAT (2017)
P = probability of getting caught P	0.2 (unless other value is specified)	ANA (2009)

d = threshold of precipitation coefficient that the system supports	13,000 MMC	ANA (2009)
b = government support	700,000 S/.	Proyecto Especial Chira-Piura (2016).
w = water tariff	0.003 (unless other value is specified)	Proyecto Especial Chira-Piura (2016).
ρ = speed of conversion from cooperator to non-cooperator	1 (unless other value is specified)	For sensitive analysis

APPENDIX I

MATLAB SCRIPT FOR CHAPTER 5

```
clear;

%set steps number for calibration = 37, for Robustness analysis = 80
steps = 37;

% Set the parameters:
%a is the coefficient of water loss in the canal or river
a = 0.01;
%l is the length of the canal or river
l = 30;
% delta is the parameter of cost of monitoring in soles
delta = 100;
% gamma = sanction
gamma = 1750;
%Infrastructure depreciation (tetta)
tetta = 0.2;
%Prob = probability of getting caught
Prob = 0.2;
%rho is the moral inertia for the replicator dynamic
rho = 1;
%Define the Damage impact of floods
damage = 13000;
%NINO Disturbance
Nino = 17000000000/1000000;
SNino = 18000000000/1000000;
% Amount in millions of Peruvian Soles of the government spend in
% infrastructure maintenance
gov = 0.7;
% Coeeficient of reaction (government expenditure) in el Nino events.
gov_react = 1.5;
%Define population upstream N1. In Piura Population Upstream is 2502,
but
%not all have rice fields and the total irrigated rice surface for 2016
is
%9170 ha. The production function is for one ha. Then for this effect I
%assume the grown ha instead of population.
N1 = 9170;
%Define population downstream N2. Population in 2016 is 14178 and ha is
%31,516
N2 = 31516;
%Calculate total population
N  = N1 + N2;
%In this case, users share water supply with other system. They take
50% of
%it
chira=0.5;
%The natural damage of el NINO  coefficient
perf_ef=20000;
%Economic Parameters q=water value in terms of crop profit, c = cost of
ag,
%r =
q=1.45*1000000;
c=0.46*1000000;
r=0.000075*1000000^2;
%Monetary units of provisioning in the solved
Munit = 1000000;
%Water tarif as a proportion of farmers income. This is the
```

```
provisioning
%proportion of income of  cooperators
water_t = 0.003;

%----------------Attention 1----------------------------------
%------------------------------------------------------------

%Activate the j loop for bifurcation analysis, remember to activate end
%of the loop too
for j=(1:11)

%for rho (the moral inertia) bifurcation
%rho = (j-1)/10;

%for Prob = probability of getting caught bifurcation
%Prob = (j-1)/10;

%for gov support bifurcation
%gov = (j*3)/10;

%for water_t bifurcation
%water_t = (j*3-3)/1000;

%for crop profitability bifurcation
%q = ((j*10-10)/10)*1000000;

%for E initial condition sensitivity
E = (j-1)/10;

%------------------------End of Attention 1-----------------------

%-------------------------Attention 2 ------------------------------
%Activate the following when no bifurcation analysis is been done
%j=1;
%----------------------------------------------------------
% Set the initial conditions:

%for E (public infrastructure performance)
%E = 0.85;
%  QS (water coming from nature)
QS_normal = 4000000000/1000000;
% fraction of cooperators upstream the system S1
S1 = 0.26;
% fraction of cooperators downstream the system S2
S2 = 0.26;


%-----------------------------------------------

for i = (1:steps)

%Choose your El NINO perturbations:

% Activate the following for Analysis of current state
```

```
if i==4 || i==19
% Activate the following for Analysis of Shocks every 15 years
%if i==4 || i==19 || i==34 ||  i==49 ||  i==64 ||   i==79
% Activate the following for Analysis of Shocks every 10 years
%if i==4 || i==19 || i==29 ||  i==39 ||  i==49  || i==59 || i==69 ||
i==79

%Activate the following for Historical Ninos
QS= Nino;
%Activate the following for Stronger Ninos
%QS= SNino;

else
    QS = QS_normal;
end



% To know how much water is there from rain and public infrastructure
(e.g.
% reservoir)

Q = max((E*QS-(1-E)*(QS^2)/damage)*chira,0);

% But there will be some water losses in the canal. Then the total
water
% available for all users (including downstream)  considers the
parameter
% of water loss "a", the lenght of the canal or river "l" and the
% performance of the public infrastructure (it is all lumped in E)

QAll = Q*(1-a*(1-E)*l);

%Managers determine the max possible individual appropriation (ul).

ustar = (q-c)/r;

%(q-c)/r is the level of water appropriation that maximize users payoff
thus users, if rational,
% wont ask more than that. ul is considered the appropriation rule
"Users
% should not appropriate more that ul"

ul = min(QAll/N,ustar);

% Users will decide how much to appropriate based on their group first
(if they are
% cooperative or not) and on their incentives second.

%We findout how many cooperator and non-cooperators are there in both
%groups (upstream - 1- and downstream - 2- )

N_c_1 = N1*S1;
N_c_2 = N2*S2;
N_nc_1 = N1*(1-S1);
```

```
N_nc_2 = N2*(1-S2);
N_c = N_c_1 + N_c_2;
N_nc = N_nc_1 + N_nc_2;

% I define how much the loss will be:

  loss = a * l * (1 - E) * Q;

%If there is enough water for everyone, then everyone just maximize
their
%profits. But if not, we have to check wether if they are upstream
(group 1) or
% downstream (group 2), how much water available is there for them, and
if
% they are cooperation ( c ) or not (nc ).



if ustar <= ul
    utotal = ustar*N;
    u_c_1=ustar;
    u_nc_1 = ustar;
    u_c_2 = ustar;
    u_nc_2 = ustar;
else

    u_c_1 = ul;
    if ustar * N_nc_1 <= Q - u_c_1 * N_c_1;
        u_nc_1 = ustar;
        if ul * N_c_2 <= Q - u_c_1 * N_c_1 - u_nc_1 * N_nc_1 - loss;
            u_c_2 = ul;
            if ustar * N_nc_2 <= Q - u_c_1 * N_c_1 - u_nc_1 * N_nc_1 -
u_c_2 * N_c_2 - loss;
                u_nc_2 = ustar;
            else u_nc_2 = max((Q - u_c_1 * N_c_1 - u_nc_1 * N_nc_1 -
u_c_2 * N_c_2 - loss)/N_nc_2,0);
            end

        else u_c_2 = max((Q - u_c_1 * N_c_1 - u_nc_1 * N_nc_1 - loss)/
N_c_2, 0);
            u_nc_2 = 0;
        end
    else u_nc_1 = (Q - u_c_1 * N_c_1 ) / N_nc_1;

        u_c_2 = 0;
        u_nc_2 = 0 ;
    end

end

%Managers decide how much users should pay based on social profit
%maximization. For that, first we make use of some variables grouping
for
%the ease of calculation
```

```
Help_A = a*l*QS + a*l/damage;
Help_B = QS - a*l*QS + (QS^2)/damage - 2*a*l/damage;
Help_D = E * (1- E);
Help_F = E*(1-tetta);
Help_G = Help_D^2 * Help_A;
Help_H = 2 * Help_F* Help_D * Help_A + Help_D * Help_B;

syms x positive
eqn = (q-r*ustar)*(((2*exp(-2/x))*Help_G)/(x^2)+(Help_H/(x^2))*exp(-
1/x))-1 == 0;
solx = solve(eqn,x);

Mt = double(solx)* Munit;

%that means that individually, they have to give mi
mi = Mt/N;

%but  cooperators will only pay if they had possitive income (before M)
and not more
%than half of it

income_c = (q*(u_c_1)-0.5*r*(u_c_1)^2-c*(u_c_1))* N_c_1 + (q*(u_c_2)-
0.5*r*(u_c_2)^2-c*(u_c_2))*N_c_2;
%if income_c > mi*N_c
%    Mr = mi*N_c;

%else
    Mr = max(income_c* water_t,0) ;
%end

%We can now calculate individual payoffs for each group
if N_c_1 ==0
pi_c_1 = 0;
else
 pi_c_1 = q*(u_c_1)-0.5*r*(u_c_1)^2-c*(u_c_1)-Mr/N_c-delta;
end

if N_c_2 ==0
pi_c_2 = 0;
else
    pi_c_2 = q*(u_c_2)-0.5*r*(u_c_2)^2-c*(u_c_2)-Mr/N_c-delta;
end

if N_nc_1 == 0
pi_nc_1 = 0;
else
 pi_nc_1 = q*(u_nc_1)-0.5*r*(u_nc_1)^2-c*(u_nc_1)- gamma*Prob;
end

if N_nc_2 == 0

    pi_nc_2 = 0;
else
pi_nc_2 = q*(u_nc_2)-0.5*r*(u_nc_2)^2-c*(u_nc_2)- gamma*Prob;
```

```
end

pi_c = pi_c_1*N_c_1 + pi_c_2*N_c_2;
pi_nc = pi_nc_1*N_nc_1 + pi_nc_2*N_nc_2;
pi_avg = (pi_c + pi_nc)/N;

%Now we activate the replicator dynamics
S1 = max(min(S1+S1*(max((pi_c_1 - pi_avg)/pi_avg,0)-rho*max((pi_avg -
pi_c_1)/pi_avg,0)),1),0);
S2 = max(min(S2+S2*(max((pi_c_2 - pi_avg)/pi_avg,0)-rho*max((pi_avg -
pi_c_2)/pi_avg,0)),1),0);

%Now we see how the performance changes

if Mr>0 &&  QS==QS_normal
    E=E+exp(-1/((Mr/Munit)+ gov))*E*(1-E)-tetta*E;

else
    if Mr==0 && QS == QS_normal
        E=E-tetta*E;

else E = E+exp(-1/((Mr/Munit)+ gov_react*gov-(QS -
damage)/perf_ef))*E*(1-E)-tetta*E;

    end
end
FracCoop_1(j,i) = S1;
FracCoop_2(j,i) = S2;
Performance(j,i) = E;
Provisioning(j,i) = Mr/Munit+gov;
UpstreamC_B (j,i) = pi_c_1;
UpstreamNC_B (j,i) = pi_nc_1;
DownstreamC_B (j,i) = pi_c_2;
DownstreamNC_B (j,i) = pi_nc_1;
time (i) = i+1980;
end

%Activate this end for the j loop
end

%Now I graph some interesting variables:
% Fraction of Cooperations
subplot (2,2,1)
plot(time,FracCoop_1,time,FracCoop_2)
title('Cooperators Fraction (Si)')
legend('S1','S2','Location','southeast','Orientation','vertical')
% Infrastructure Performance
subplot (2,2,2)
plot(time,Performance)
title('Hard Infrastructure Performance (E)')

%Infrastructure Provisioning
subplot (2,2,3)
plot(time,Provisioning)
title('Hard Infrastructure Provisioning ')
```

```
%Farmers Benefits
subplot (2,2,4)
plot(time,UpstreamC_B,time, UpstreamNC_B,time,DownstreamC_B, time,
DownstreamNC_B)
title('Farmers Benefits')
%legend('Pi 1 C','Pi 1 NC', 'Pi 2 C', 'Pi 2
NC','Location','southeast','Orientation','vertical')
```