A SYSTEMS APPROACH TO SUSTAINABLE RURAL WATER INFRASTRUCTURE IN DEVELOPING COUNTRIES

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ABSTRACT

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A Systems Approach to Sustainable Rural Water Infrastructure in Developing Countries

Dissertation directed by Dr. Bernard Amadei

Failure of rural water infrastructure in developing countries is often caused by the systemic interaction of technical, social, financial, institutional, and environmental factors. Unfortunately, current approaches for the planning and evaluation of sustainable rural water services in developing countries are unable to adequately interpret and adapt to the complex interactions of these factors. Thus, the aim of this research was to investigate a systems approach to better consider these inherent complexities through modeling the systemic interaction of influential factors. The overarching research question asks *how do factors interact as a system to influence rural water system sustainability in developing countries*? To answer this question, this research began with a systematic review of water sector literature to identify factors that influence the long-term functionality of rural water infrastructure in developing countries. Through this systematic literature review, it was possible to identify a list of important factors the author called “sustainability factors”. Using a panel of water sector experts involved in Delphi survey and cross impact questionnaire study, it was then possible to model the interaction of these sustainability factors as a system. The culmination of this work (Chapter 2) presented a causal loop diagram that described the critical areas of factor interaction by identifying dominant feedback mechanisms. The dominant feedback mechanism was found to influence water system functionality through the community involvement with system maintenance, proper finances for operation and maintenance, and effective water system management. However, the study also found a multitude of feedback mechanisms that could be equally influential within a particular regional context.

Thus, the next step of this research entailed the use of focus groups to gather opinion-based data on factor interaction from water project stakeholders in Terrabona, Nicaragua. This work (Chapter 3) allowed for context-based evaluation of factor influences in the form of stakeholder value networks. Specifically, this study presented a compelling use of systems diagramming to gain insight into stakeholder alignment. This study ended with a petition for future research that would verify whether these stakeholder value networks truly provide accurate representations of stakeholder alignment compared with the true interaction of factors that influence rural water system functionality in the field. As such, the last step of this research was to identify field-based factor interaction using field-based evidence from water systems in Darío and Terrabona, Nicaracua (Chapter 4). Using graphical modeling, this last study used interview data gathered from water committee members to build factor networks based on conditional dependence between factors. The study showed a dramatic difference in factor interaction between Darío and Terrabona, and demonstrated the impact of regional context on factor influence. In summary, this doctoral research presents both practical and theoretical contributions to the field of rural water development by demonstrating the usefulness of systems-based methods to understand project complexity. Future research, which further tests the ability of these tools to predict project success and foster holistic learning, will certainly prove a worthy endeavor for future researchers and practitioners.

ACKNOWLEDGMENTS

The dissertation you are about to read is not solely my own work, but the cumulative product of hours upon hours of guidance, editing, and “wordsmithing” from my advisors and colleagues. Truly, it is quite possible that every word you read in this dissertation has been somehow ***touched*** and ***inspired*** by more than 6 other people. And, let us not even begin to acknowledge the many scholars I have been inspired by, whose words I have quoted, and whose shoulders I have stood on to see farther – or merely look down from to see – to my dismay – how far I have climbed without a rope. It is my honest opinion that each and every individual within Amy and Paul’s research groups (including Maryanne Fantalis!) should place their name on this document right next to mine, and be given an honorary doctorate.

The words in this dissertation pay insufficient homage to the hidden ***stories*** it could tell if given the chance. It would tell of my personal doubt and crippling despair that at times left me paralyzed and unable to do this research. It would tell of innumerable red-eyed mornings at Bittersweet in Louisville drinking coffee that was, ironically, quite bitter, but not all that sweet. It would tell of the frequent days my wife Jessie and daughter Rayna had to “understand” I was working. It would tell of the laughter in the grad office about some stupid (and yet glorious) YouTube video of screaming goats and Taylor Swift; how so often my wrinkled and tired brow would be given much needed respite by a light-hearted belly-laugh with my colleagues. It would tell of the successes and failures of each of the papers within the main dissertation body; of the down-right mean comments of blind reviewers; and the encouraging accolades from people that kept me going.

Indeed, the typed words in this dissertation are a façade, a shell, covering ***richer*** things with academic lingo and form:

– The richness of ***meeting*** with my advisor, Dr. Bernard Amadei, and co-advisors, Dr.Paul Chinowsky, and Dr. Amy Javernick-Will; meeting with Bernard to passionately discuss the implications of systems-thinking for sustainable development, a topic he inspired me to investigate some 3 years ago; meeting with Paul to gain invaluable wisdom about what it takes to be a good academic and father; meeting with Amy to be inspired to write better, to work harder, and to stay on track. Truly, I owe more to Amy than there are words to do justice, and hope she knows by now how impactful she is in the lives of her students.

– The richness of connecting and ***learning*** important lessons from my colleagues in the grad lounge, the C4C, the CEM office, and ECCE161 grad citadel; learning from Kaitlin, John, and Jessica about what it takes to write a rigorous research paper, while keeping an eternal perspective; learning from Xavi, Cristina, and Wesam that academia is a world-wide pursuit towards excellence; learning from Amy, Sarah and (Real) Laura how life-giving baked goods and Keurig coffee can be; and, learning from Kyle how meaningful and impactful it can be to have a hetero-life-partner in the office during times of tribulation.
– The richness of depending on my friends and family, and ***leaning*** on them for support over these past years; leaning on my father for his unwavering support during my tumultuous time in college, appreciating that he frequently (but not always) abstained from singing George Thorogood's "Get a Haircut" –"get a haircut, and get a real job"; leaning on Jessie, a person I love and respect more than I could have ever imagined, the cornerstone of our family; leaning on Pat, Justin and the rest of my Rootz BOCs, who bi-weekly (to Pat's chagrin) give me encouragement and flatulence-induced laughter.

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CHAPTER 1 INTRODUCTION

"Obviously, prospective thinking has to be global: very few problems can be isolated; on the contrary, problems are becoming increasingly interdependent and indeed, increasingly entangled. It is therefore essential to use methods based on systems analysis: this method enables the integration, in respect of the whole complexity of their relationships, all types of processes, conflicts and challenges".

-Michel Godet 1986

"Let me hope that [complex] *ideas and orientations…will be understood and internalized by policy-makers and others with power, as well as by researchers, analysts and managers; that this will lead to norms, actions and relationships that will make development and humanitarian practice more attuned to reality, more sensitive to context, more adaptive, less reductionist and less simplistic; and that this will in turn generate and enable changes that enhance social justice and are more effectively pro-poor."*

-Ramalingham 2008

OBSERVED PROBLEM

In the developing world, over 768 million people are without access to safe drinking water, 83% of which live in rural communities (JMP 2014). Despite well-intended efforts, intervention attempts to sustainably lower these statistics have been largely unsuccessful. Studies have shown between 30% and 50% of rural water projects, whether water systems, wells or point-of-use systems, fail between 3 and 5 years following construction (WASH Sustainability Charter 2013).

In response to this problem, the international water sector has spent over two decades focusing on the *factors* that may impact the sustainability of rural water services, with the intent that discerning these factors may lead to improvements in existing and future rural water planning and management schemes. Specifically, studies have been undertaken to identify, understand and measure such factors as community participation (Narayan 1995; Marks and Davis 2012), the feasibility of financial management schemes (Whittington 1990), user demand (Davis and Marks 2012; Whittington et al.

2009), supply chain management (Harvey and Reed 2007), environmental resource management (Mackintosh 2003; McConville 2006; Srikanth 2009), and to evaluate water service sustainability (Sugden 2003; Lockwood et al. 2003; Lockwood & Smits 2011; Godfrey et al. 2009; Godfrey et al. 2013; USAID 2013). These studies have made significant progress in identifying the factors that can affect sustainability (i.e., permanent or "long-term functionality") of rural water services, and some have combined these factors into evaluation frameworks. Unfortunately, the methodologies these frameworks use to assess the interaction of factors do not consider factor interaction as a system, and this assessment is typically overly simplified through reductionist approaches of linear scoring or regression analysis.

This simplification of the interaction of factors potentially leads to a limited and narrow understanding of sustainability by failing to consider the systemic interaction of factors that largely affects the functionality of water services (Sara and Katz 1997; Sugden 2003; Lockwood et al. 2003, Richardson et al. 2011; Sterman 2000; Ramalingham 2008, 2014; Breslin 2004; Amadei 2015). As a result, this research posits that rural water planning schemes based on reductionist frameworks inadequately provide the means to consider, interpret and adapt to the systemic interactions of technical, social, financial, institutional, and environmental factors that influence service sustainability (Lockwood et al. 2003; Sugden 2001, 2003). As the United Nations High Level Panel on Global Sustainability (2012) states: "Sustainable development is not a destination, but a dynamic process of adaptation, learning and action; it is about recognizing, understanding and acting on interconnections" (p.21). Thus, in order to create sustainable solutions to water poverty, these complexities must be elucidated in processed-based terms that more aptly describe the systemic and inherently complex influence of factors that affect sustainability (Baghari and Hjorth 2007; Veeman and Politylo 2003; Berke and Conroy 2000; Cary 1998, Kerkhoff 2006; UN 2012; Lockwood 2003; USAID 2014). Therefore, the gap in knowledge and practice this research aims to address is: ***the proper planning of rural water***

infrastructure must consider the systemic interaction of factors that affect rural water service sustainability.

Tightly coupled with the planning of long-lasting rural water services is the strategic alignment of key stakeholders who plan and manage rural water systems. In reality, proper rural water service development not only requires a holistic understanding of the systemic interaction of factors that influence sustainable water services, but also requires an understanding of how these factors and resources influence stakeholder coordination or alignment on a particular project (Amadei 2014). Indeed, a litany of experts, specifically highlighting global water aid challenges, cite incongruous alignment between donors, country-level organizations and governments as a major cause of water system failure (BN 2012; WaterAid 2011; Williamson 2008; Ferguson 2004). It is clear that stakeholder alignment is intermixed within the aforementioned complexities inherent in rural water development, and cannot be decoupled from the process of forming a systems-based understanding of sustainability. Thus, understanding how project stakeholders coordinate with one another and align with complex realities in the field was a complementary and practical application of the research presented in this dissertation.

CLAIMED CONTRIBUTIONS

The three papers that make up the body of this dissertation (Chapters 2 through 4) address the previously mentioned gap in literature by exploring a multi-method systems approach to identify and explore the interaction between factors that affect rural water service sustainability in developing countries. Through this process, this dissertation contributes three distinct findings to the body of knowledge. First, it presents evidence of systemic factor interaction by illuminating such factor interaction within multiple contexts. Thus, it demonstrates a clear need for the international water sector to consider sustainability in process-based terms, rather than as a static outcome, in theory and in practice. Second, it provides a novel application of systems-based techniques to quantitatively evaluate stakeholder alignment. Third, it presents a useful technique for creating factor network diagrams using field-based data (interviews and observations) and probabilistic graphical modeling as a means to represent how factors interact as a system based on realities in the field. In a culmination of these three contributions, this dissertation concludes with a framework that uses participatory (opinion-based modeling) in combination with case study data collection (field-based modeling) that allows practitioners to improve strategic planning decisions by considering the systemic complexities inherent in rural water development.

DISSERTATION SUMMARY

The objective of this research was to investigate an approach to understanding the systemic interaction of factors found to influence the long-term functionality of rural water systems in developing countries. To accomplish this primary objective, this research used data based on the *opinions* of water sector experts who participated in a Delphi panel and survey questionnaire; data based on the opinions of four key water project stakeholder groups in Nicaragua gathered in focus groups; and *field* data gathered through community water committee interviews and observations conducted in rural Nicaragua. These data were separately analyzed and interpreted within three papers presented in the body of this dissertation as Chapters 2, 3 and 4.

In the studies presented in Chapters 2 and 3, cross impact analysis and qualitative system dynamics diagramming were used to take opinion-based data and develop factor influence *diagrams* and *networks* for the experts and the Nicaragua stakeholders, respectively. Factor diagrams and networks were then used to analyze factor interaction based on structural analyses using qualitative system dynamic modeling and the betweenness centrality measure. Opinion-based factor networks, called "stakeholder factor networks" for the water project stakeholders also permitted alignment comparisons based on the structural differences in the four stakeholder factor networks for each stakeholder group. The results for these opinion-based studies are shown in Chapters 2 and 3.

Three primary findings resulted from the opinion-based studies. First, analysis of factor diagrams and networks for experts and stakeholders showed the most important factor for long-term water system functionality was "Finances:" that is, that enough funds were continually available to properly operate and maintain the water system. Second, given the apparent complexity demonstrated within the expert and stakeholder factor diagrams (based on the number of factor influences and feedback mechanisms, respectively), it was seen that factor importance could easily vary in different contexts (country, cultural, management scheme, etc.). The importance of context was reiterated by comments from expert panelists who expressed their difficulties in generalizing factor influence given the nuanced aspects of rural water service sustainability. These results showed that context matters with systems diagramming, a generally agreed upon premise in systems literature (Ramalingham 2008). Third, the study in Chapter 3 demonstrated a practical application of systems diagramming to gain insight into stakeholder alignment.

In the study presented in Chapter 4, case study (field-based) data was used to make important distinctions between opinion-based factor structures as they compare to factor structures based on the contextual realities in Terrabona and Darío, Nicaragua. These data, in the form of water committee interviews and field observations, allowed for the identification of emergent factors through the qualitative coding of transcribed interviews and observation notes. In total, 33 communities were sampled in Darío and 18 in Terrabona. Probabilistic graphical modeling was then used to build factor network diagrams based on the conditional dependencies present between these emergent factors for each community.

In Chapter 5, the factor networks and their structural properties are compared among all the different data sources (experts, stakeholders, case study) used in Chapters 2 through 4, and a summary of those differences, as well as the associated implications thereof, are presented. Finally, a participatory evaluation framework is presented, which uses opinion-based and field-based data to build systems-based knowledge on the complexities of rural water development for a particular regional context. More detail on this evaluation framework may be found in Appendix F, and a summary of this dissertation is provided below in Figure 1-1.

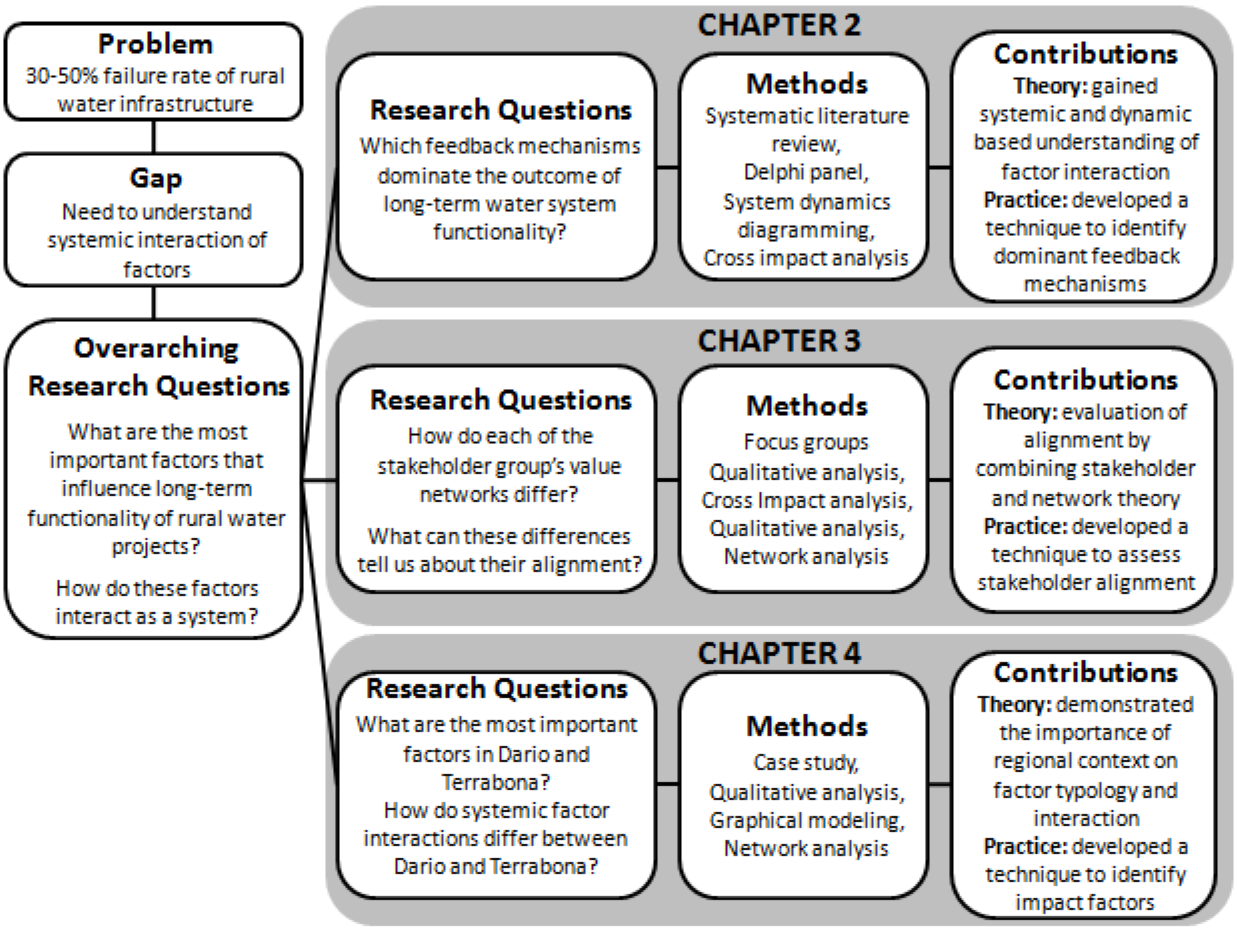

Figure 1-1: Dissertation summary

RESEARCH QUESTIONS

The research presented in this dissertation aims to increase the scope of knowledge on the systemic influence of factors that affect the sustainability of rural infrastructure in developing countries. Specifically this requires answering the following overarching research questions: *What are the factors that influence long-term functionality of rural water services? How do these factors interact as a system?* This research sets out to answer these questions through the collection and analysis of three forms of data: (i) expert opinion (Chapter 2), (ii) stakeholder opinion (Chapter 3), and (iii) case study data (Chapter 4). Additionally, the body chapters (Chapter 2 through Chapter 4), answer questions specific to each data type. Each of these chapter-specific research questions is outlined below designated by chapter number and chapter-specific research question (for example, the first research question of Chapter 2 is designated as RQ2-1).

<u>Chapter 2 –Water Sector Experts Research Questions:</u>

The first step in this research involving water sector experts did not engage the experts themselves, but rather involved a literature review to identify the factors that would later be presented to these experts. Specifically, this systematic literature review set out to answer the question:

RQ2-1: What are the most important factors that influence the long-term functionality of rural water infrastructure in developing countries?

The next step was to hypothesize and identify how these factors interact as a system to affect rural water system functionality, based on expert opinion. Thus RQ2-2 asks:

RQ2-2: How do these factors interact as a system?

Once the factors and their connections were identified, the next step was to hypothesize and identify the dominant feedback mechanisms using the interactions indicated by the experts:

RQ2-3: Which feedback mechanisms dominate the outcome of long-term water system functionality?

<u>Chapter 3 –Stakeholders Research Questions:</u>

Next, this research focused on the structural comparison factor interaction indicated by stakeholders in Terrabona, Nicaragua, in order to understand how factors interact within a particular regional context. To develop a theoretical basis for stakeholder alignment (Chapter 3), these factors were termed *values*, which are important project aspects stakeholders feel are necessary to sustain rural water services. Thus, the first research question is:

RQ3-1: What are the values of stakeholder groups involved in the management of rural water infrastructure in Terrabona, Nicaragua?

Once the stakeholder values were identified, the next step was to illuminate value interaction to build value networks. The research question that accompanies this step is:

RQ3-2: How are these values structurally connected as a network?

With value networks built, the next step was to structurally analyze these networks, where the question associated with this step is:

RQ3-3: How do each of the stakeholder groups' value networks differ?

RQ3-4 then relates to how the value networks identified by the stakeholders compare. Specifically, this question relates to the alignment (or non-alignment) between different stakeholders based upon how values structurally interact:

RQ3-4: What can these differences tell us about their alignment towards the end-goal of long-lasting water services?

Chapter 4 –Case Study Research Questions:

Lastly, Chapter 4 focuses on the comparison of factor networks for Darío and Terrabona Nicaragua using field data. First, this study investigates the factors that influence water service sustainability, asking the question:

RQ4-1: What are the factors that influence functionality of rural water services in Terrabona and Darío, Nicaragua?

The next step was to identify how the factors in Darío and Terrabona form an interconnected network, by asking the question:

RQ4-2: How do these factors form interconnected networks?

With factor networks built, the next step was to analyze the structure of these networks to identify the most influential factors, where the associated research question is then:

RQ4-3: Based on an understanding of factor interaction as a network, what are the most important factors for long-term functionality of rural water services in Darío and Terrabona?

Lastly, RQ4-4 relates to how factor structures compare between Darío and Terrabona. The question of interest pertains to how area context influences structural differences in factor interaction (and vice versa) and how this can inform management strategies for future rural water infrastructure in these two municipalities. Thus, the research question becomes:

RQ4-4: How do systemic factor interactions differ between Darío and Terrabona?

Table 1-1 provides a summary of these research questions in their order of appearance in the body of this dissertation.

Table 1-1: Overview of research questions

Chapter	Research Question
2	*RQ2-1: What are the most important factors that influence the long-term functionality of rural water infrastructure in developing countries?*
	RQ2-2: How are these factors interact as a system?
	RQ2-3: Which feedback mechanisms dominate the outcome of long-term water system functionality?
3	*RQ3-1: What are the values of stakeholder groups involved in the management of rural water infrastructure in Terrabona, Nicaragua?*
	RQ3-2: How are these values structurally connected as a network?
	RQ3-3: How do each of the stakeholder groups' value networks differ?
	RQ3-4: What can these differences tell us about their alignment towards the end-goal of long-lasting water services?
4	*RQ4-1: What are the factors that influence functionality of rural water services in Terrabona and Darío, Nicaragua?*
	RQ4-2: How do these factors form interconnected networks?
	RQ4-3: Based on an understanding of factor interaction as a network, what are the most important factors for long-term functionality of rural water services in Darío and Terrabona?
	RQ4-4: How do systemic factor interactions differ between Darío and Terrabona?

RESEARCH METHOD OVERVIEW

Answering the aforementioned research questions required a multi-method approach that culminates with qualitative system dynamic modeling, network analysis, and graphical modeling. These methods worked together to elucidate factor interaction (or structure) as they related to the different data sources. In Chapter 2 of this dissertation, the systemic and dynamic interaction of sustainability factors in the form of emergent feedback mechanisms were investigated using the input from water sector experts. In Chapter 3, water project stakeholders in Terrabona were engaged in focus groups to identify systemic factor interaction used to judge stakeholder alignment. In Chapter 4, interview and observational data are used to construct field-based factor interaction networks using probabilistic graphical modeling. A graphic highlighting the flow of these methods throughout the dissertation is shown in Figure 1-2. The research methods used for data collection and analysis are then briefly summarized in Table 1-2.

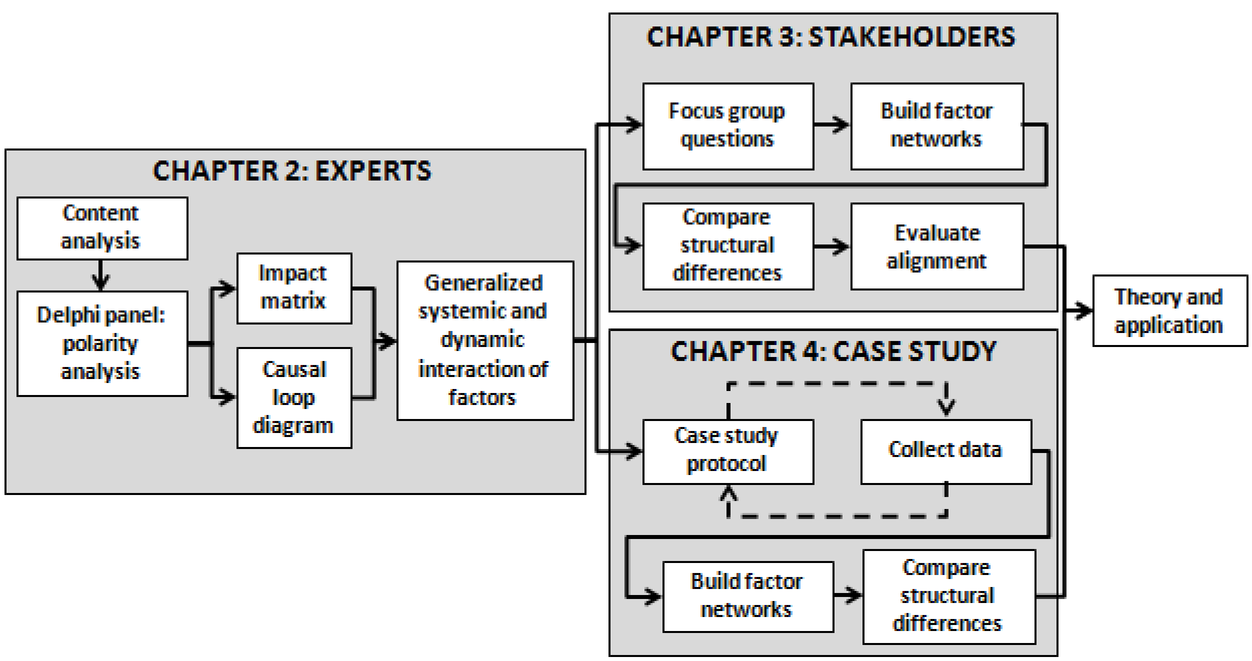

Figure 1-2. Overview of research methods

DATA COLLECTION

<u>*Content Analysis*</u> [Chapter 2]

A *content analysis* was performed (Chapter 2) to rigorously identify factors that influence the long-term functionality of rural water services. This was conducted by searching within scholarly journals and journals published informally within the water sector using different combinations of the keywords “rural water”, “developing countries”, “sustainability”, “factors” and “indicators”. Scholarly articles were searched within the “Web of Knowledge” and “Engineering Village”. The process began by reading the abstract of each article found in the keyword search to ensure the research premise was related to rural water service sustainability in developing countries. Articles that did not meet this requirement were excluded. Factors in the literature said to affect the sustained functionality of a rural water system in a developing country context were coded. Finally, these coded factors were grouped within affiliated categories called “sustainability factors”. The factors identified were: Community, Government, External Support, Management, Environment & Energy, Finances, Technology, Construction & materials, and Water System Functionality. These factors were used in all subsequent analyses using the opinions of water sector experts in Chapter 2. A summary of the sources used in the content analysis as well as the complete list of factors and sub-factors may be found in Appendix A.

<u>*Delphi Method, Polarity Analysis*</u> [Chapter 2]

The *Delphi Method* is a research technique used to facilitate consensus within a group of experts regarding underlying relationships among causal factors (Linstone and Turoff 1975; Gratch 2012; Hsu et al. 2007; Ludwig 1997). This is typically done through a multi-round survey whereby panelists are presented (typically remotely through online-survey) in each subsequent round with the aggregate group responses from the previous round in an attempt to facilitate consensus on a particular theme. This research used the Delphi Method with a panel of water sector experts to attempt consensus on the systemic and dynamic interaction between the sustainability factors found in the content analysis. This entailed asking panelists to indicate both the presence of influence, as well as the polarity of influence (*polarity analysis*) between factors. Polarity of influence was indicated as either positive (+: an increase in Factor A causes an increase in Factor B), or negative (-: an increase in Factor A causes a decrease in Factor B). The Delphi was completed in two rounds, and consensus was reached on 42 of the 56 possible factor influences. These results are analyzed in Chapter 2, and the raw data are presented in Appendix B.

Focus Groups [Chapter 3]

Focus groups provide an open forum where people are asked questions regarding their attitudes, beliefs and perceptions (Stewart 2015). This research employed focus groups to gather opinion-based data from key water project stakeholders regarding factors and their interaction (Chapter 3). Water project stakeholders chosen for these focus groups were local government officials, community water committee members, leaders within a large organization, and local academics, all within the municipality of Terrabona, Nicaragua. These stakeholders were specifically asked to indicate which factors were the most important for long-term rural water system functionality, and then to indicate the pairwise influence between these factors. The result from these focus groups was a factor interaction diagram for each stakeholder group called a *stakeholder value network,* which was used in the subsequent analyses to judge alignment based on structural differences in value interaction.

Case Study Method [Chapter 4]

The case study method of qualitative data collection was chosen for its ability to effectively provide rich process-based data and gain insight into research questions that are primarily exploratory in nature (Yin 2009; Miles and Huberman 1994). Specifically, the case study method was used in Chapter 4 to gather field data related to the factors that influence rural water system functionality in Darío and Terrabona, Nicaragua. The case study was guided by a case study protocol based on content analysis and causal loop diagram (CLD) created in Chapter 2. Data collection took place through semi-structured interviews with community water committee members and observations taken by the author. In total, 32 communities were sampled in Darío, and 18 communities were sampled in Terrabona. More information regarding this case study may be found in Chapter 4, with a full summary of the data collection materials available in Appendix C.

DATA ANALYSIS

Cross Impact Analysis [Chapter 2]

An additional survey was conducted (Chapter 2) after the Delphi study with the same group of experts to obtain information regarding the causal strengths between sustainability factors. This was done to allow for feedback mechanism prioritization based on influence strength. The method used to gather these data was *cross impact analysis* (CIA), used for its ability to define the structure of the relationships and forces in instances where hard data are not available (Turoff 1975; Schuler et al. 1991). Performing a Cross Impact Analysis entailed defining the strength between sustainability factors through the creation of an "impact matrix" which organizes the pairwise interaction strength between these factors (Duperrin and Godet 1973). To create this impact matrix, panelists were asked to indicate the strength of influence between sustainability factors by filling out a 8 x 8 impact matrix (for the 8 sustainability factors) using the scoring scheme of non-existent (0), weak (1), medium (2), and strong (3)(Duperrin and Godet 1973; Torres and Olaya 2010; Julius 2002; Monto 2005). Influence strengths were then used to identify dominant feedback mechanisms. The impact matrices for each factor are shown in Appendix B.

Qualitative System Dynamic Modeling [Chapter 2]

The result from the Delphi and polarity analysis was an influence diagram known as a causal loop diagram (CLD), which was used to identify the emergence of feedback mechanisms, a process known as *qualitative system dynamics modeling* (Vennix 1996; Wolstenholm 1990). The general goal of qualitative system dynamics modeling is to develop and analyze the CLD, which describes the causal structure hypothesized to drive the dynamic behavior of a system through the identification and characterization of feedback mechanisms. 101 feedback mechanisms, all of which have positive polarity, were systematically identified in this research using Ventana Systems Inc.'s VENSIM program. The implications of these feedback mechanisms allowed for useful contributions to sustainability theory regarding dynamic factor interaction. Additionally, the final CLD served as a conceptual framework from which a case study protocol was created to inform data collection in Chapter 4, as described in the data collection guides provided in Appendix C (Miles and Huberman 1994).

Qualitative Coding and Factor Quantification [Chapters 3 and 4]

Audio recordings from the focus group, interviews, and observational notes recorded by the author were transcribed and analyzed using qualitative coding to identify and generalize emergent factors that influence the long-term functionality of rural water infrastructure. The process of qualitative coding entailed the systematic dissection of emergent themes or patterns from these transcribed documents for use in subsequent analyses (Miles and Huberman 1994). Coding was facilitated with the qualitative analysis software QSR NVivo 10 (QSR International Ltd., 2012). For Chapter 3, coding focused on using stakeholder language to generalize factors to later be used for alignment comparisons. For Chapter 4, the coding process involved the identification of emergent factors that appeared to influence water infrastructure based on the responses of water committee interviewees. This process then proceeded with the quantification of these factors into a binary form based on the "presence" or "absence" of a particular factor on a community-by-community basis. These binary data were then used to create factor networks using *graphical modeling*. More information on the rationale and processes used for qualitative coding and factor quantification may be found in Chapters 3 and 4, and the raw data is displayed in Appendix C.

Graphical Modeling [Chapter 4]

Graphical Modeling is a multi-variate analysis technique used to create network graphs that display conditional dependencies between model variables (Whittaker 1990). Network graphs use vertices or "nodes" to represent model variables, and lines or "edges" to represent conditional dependencies. Graphical modeling was used in Chapter 4 to empirically create factor networks similar to those created with opinion-based data, but instead using the quantified factor data from the aforementioned coding and quantification of interview data. Creating factor networks in this way permitted structural analysis of factor interaction for Darío and Terrabona, Nicaragua, based solely on realities in the field. Factor networks were created using the binary factor data within R-Project Statistical software. Networks for Darío and Terrabona were then structurally analyzed using *network analysis*. Results for this study may be found in Chapter 4, and an overview of graphical modeling theory along with the calculations for graphical models to form factor networks using R-Project, is shown in Appendix D.

Network Analysis [Chapters 3 and 4]

Network analysis is a diagramming methodology based on graph theory used to understand structural interaction and process-based relationships between variables (Scott 2000; Wasserman and Fraust 1994; Borgatti 2005). Network analysis was used to perform structural analyses of stakeholder value (Chapter 3) and factor (Chapter 4) networks. Specifically, *betweenness centrality* – a measure that scores nodal or "point" importance based on said node's ability to bridge the shortest path (geodesic) between other nodes – was the measure chosen to identify structural differences related to individual value and factor centrality in the value and factor networks (Freeman 1977). *Betweenness centralization* – a measure that scores the network as a whole based on the difference between the most central node and other nodes – was chosen to identify global differences in value and factor network structures (Freeman 1979). In Chapter 3, both betweenness centrality and centralization were used to identify different aspects of stakeholder alignment based on alignment between stakeholder values and alignment between stakeholder groups. In Chapter 4, both betweenness centrality and centralization were used to compare and contrast factor importance, and differences in overall network structure, respectively. These structural comparisons served as a basis for the findings in both Chapter 3 and 4, and are summarized in Chapter 5.

Table 1-2: Research methods overview by chapter

Chapter	Research Method	Data Source
2	Content analysis Delphi Cross impact analysis System dynamics diagramming	Scholarly/Non-scholarly journals Expert opinion
3	Focus groups Cross impact analysis Network analysis	Stakeholder opinion
4	Interviews and observations Qualitative coding and analysis Graphical modeling Network analysis	Community water committees members Field observations

PROPOSAL FORMAT

This dissertation follows a "journal article" format, where Chapters 2, 3 and 4 are stand-alone articles. Chapter 2 and Chapter 3 have been published in *Environmental Science and Technology* and the *International Journal of Sustainable Development and World Ecology*, respectively, and at the time of submission of this dissertation, have been posted online ahead of print (Walters and Javernick-Will 2015A, 2015B). Lastly, Chapter 4 has been submitted to the journal *Technological Forecasting and Social Change*, and a response is pending (Walters and Chinowsky 2015). The author respectfully requests that any citations to the work presented in Chapters 2 through 4 make reference to those published versions rather than to this dissertation.

Each of these papers contains different subject matter formatting based on the requirements from the publisher. The overall styling format of this dissertation (margins, spacing, figure labels, etc.), however, will be kept consistent. Chapter 5 provides a summary of the major findings and conclusions from all three papers and highlights both the theoretical and practical contributions of this dissertation. Additionally, Chapter 5 introduces a pilot systems-based framework (Appendix F) for factor analysis and sustainability assessment for use by water practitioners. The content in Chapter 5 and Appendix F may also be published later, but at this time serves to solely present the theoretical and practical contributions of this research as well as a call for future research. Finally, appendices included at the end of this dissertation contain additional details regarding data collection tools, R-Project code, IRB approvals, and the aforementioned framework, that could not be included in the papers due to space limitations.

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CHAPTER 2 – LONG-TERM FUNCTIONALITY OF RURAL WATER SERVICES IN DEVELOPING COUNTRIES: A SYSTEM DYNAMICS APPROACH TO UNDERSTANDING THE DYNAMIC INTERACTION OF FACTORS

Keywords: *sustainability factors; developing countries; rural water projects; modeling; systems*

ABSTRACT

Research has shown that sustainability of rural water infrastructure in developing countries is largely affected by the dynamic and systemic interactions of technical, social, financial, institutional, and environmental factors that can lead to premature water system failure. This research employs system dynamics modeling, which uses feedback mechanisms to understand how these factors interact dynamically to influence long-term rural water system functionality. To do this, the research first identified and aggregated key factors from literature, then asked water sector experts to indicate the polarity and strength between factors through Delphi and cross impact survey questionnaires, and finally used system dynamics modeling to identify and prioritize feedback mechanisms. The resulting model identified 101 feedback mechanisms that were dominated primarily by three and four-factor mechanisms that contained some combination of the factors: Water System Functionality, Community, Financial, Government, Management, and Technology, implying these factors were the most influential on long-term functionality. These feedback mechanisms were then scored and prioritized, with the most dominant feedback mechanism identified as: Water System Functionality – Community – Finance – Management. This study showcases a way for practitioners to better understand the complexities inherent in rural water development using expert opinion, and indicates the need for future research in rural water service sustainability that investigates the dynamic interaction of factors in different contexts.

INTRODUCTION

In the developing world, over 768 million people are without access to safe drinking water, 83% of which live in rural communities (JMP 2013). However, despite well-intended efforts, a large number of intervention attempts to sustainably lower these statistics have been unsuccessful. Studies have found that 30% to 50% of rural water projects, whether water systems or wells, fail between 3 and 5 years following construction (WASH Sustainability Charter 2013).

Water sector literature has shown that sustainability is often hindered as a result of the dynamic and systemic interactions of technical, social, financial, institutional, and environmental factors that influence project success or failure over time (Sara and Katz 1997; Sugden 2001, 2003; WaterAid 2011). More than just a static outcome, rural water project sustainability appears to be a process that emerges as a result of the systems-based integration of these factors (Lockwood et al. 2003; Forrester 1962; Bossel 2007; Bagheri and Hjorth 2007; Veeman and Politylo 2003; Berke and Conroy; UN 2012). As such, planning for sustainable rural water services largely becomes a process of interpreting and adapting to the dynamic interaction of factors that influence long-term functionality (Lockwood et al. 2003). Thus, in order to create long-lasting solutions to water poverty, the systemic and dynamic interaction between these factors must be considered.

Literature within the international water development sector are rich with studies investigating the causes of water system failure. For instance, literature has shown communities often lack the necessary capacity to maintain their water system (IRC 2009), with wells breaking down frequently due to poor maintenance or insufficient water supplies caused by seasonal fluctuations in water levels (UNICEF Sierra Leone 2012). In addition, water systems often fail to respond to local needs, desires, and demands, leading to eventual abandonment of the water system (Chatterley 2012; Lockwood and Smits 2011). And, finally, a lack of harmonious coordination and alignment between donors, non-governmental organizations, and key stakeholders, coupled with an inefficient use of resources, often stifles effective capacity building of the community, government, and local institutions (Chatterley 2012; Lockwood and Smits 2011; Baumann and Danert 2008; Ferguson and Mulwafu 2004; Nyirishima and Mukasine 2011). These examples, and many others, provide evidence of the complex interaction of technical, political, social, financial, institutional, and environmental influences that can lead to water system failure.

In light of these failures, the sector has developed evaluation frameworks that use factors and indicators to assess sustainability of existing and future water projects and programs. Indicators have been used to understand and measure levels of community participation (Narayan 1995; Marks and Davis 2012), the feasibility of financial management schemes (Whittington 1990; Abramson et al. 2011), user demand and willingness to pay(Whittington 1990; Abramson et al. 2011), supply chain management (Harvey and Reed 2004, 2007), and environmental resource management (Harvey and Reed 2004, 2007) , and to evaluate water service sustainability (Abrams et al. 2006; Jones and Silva 2009; Godfrey et al. 2009; Godfrey et al. 2013; USAID 2013). However, while these studies have made significant intellectual contributions, evaluating the interaction of factors in this static way may limit our understanding of sustainability by not considering their dynamic interaction (Sara and Katz 1997; Sugden 2003). Thus, this study aimed to investigate a means to extend existing knowledge on sustainable rural water service provision by considering the dynamic and systemic interaction of factors.

To understand the dynamic interaction of factors that influence long-term rural water system functionality, this study employed a mixed-methods approach that culminated with system dynamics modeling. System dynamics modeling offers a way to understand the systemic and dynamic nature of complex problems through the identification of closed-system interaction between factors known as *feedback mechanisms*, which are hypothesized to drive system behavior (Churchman 1968; Richmond 2001; Sterman 2000; Meadows 2008; Pruyt 2013; Vennix 1996). Thus, this study was guided by the system dynamics modeling process that included identifying factors that influence long-term functionality of rural water infrastructure in developing countries and determining the dynamic interaction of these factors by identifying feedback mechanisms. Using these methods, the study set out to specifically answer the questions: *What are the most important factors that influence the long-term functionality of rural water infrastructure in developing countries? How do these factors interact as a system? Which feedback mechanisms dominate the outcome of long-term water system functionality?* By answering these questions, this study aims to improve sector knowledge on sustainability by gaining much needed insight regarding the dynamic and systemic complexities inherent in rural water project sustainability. Additionally, it aims to motivate future research focused on finding solutions and remedies to rural water issues in developing countries that are dynamic and systemic in nature.

METHOD & RESULTS

As indicated previously, system dynamics modeling allows us to analyze feedback mechanisms that form through the dynamic interaction of factors. These feedback mechanisms help determine what drives an outcome; in this case the success or failure of a rural water project (Sterman 2000; Meadows 2008; Pruyt 2013; Vennix 1996). Therefore, system dynamics modeling not only allows a better understanding of the complex structure of factors and influences that lead to a particular problem, but also provides a way to learn from, adapt to, and plan for unintended consequences that could result from a particular solution (Meadows 2008; Vennix 1996; Sterman 2000). Following its inception in 1961 by Michigan Institute of Technology (MIT) professor, Jay Forrester, system dynamics modeling has been used for a wide range of applications. For example, there is a long tradition of using system dynamics to study public management issues (Homer 1985), including public health (Homer 1985; Newman and Martin 2003), energy and the environment (Bossel 2007; Ford 1999), social welfare (i.e., modeling the war on drugs)(Sterman 2000; Homer 1993), security (Weaver 2006), economics and enterprises(Churchman 1968; Sterman 2000), and sustainable development (Bossel 2007; Meadows 2008; Vennix 1996; Saeed 2001).

System dynamics modeling can entail qualitative or quantitative modeling. Typically, qualitative system dynamics modeling precedes quantitative modeling (Vennix 1996; Wolstenholme 1990). The primary objective of qualitative system dynamics modeling is to develop dynamic theory, traditionally in the form of a causal loop diagram (CLD), which visually depicts the causal structure hypothesized to drive the dynamic behavior of the system. In this case, dynamic behavior manifests in the emergence of feedback mechanisms, where a feedback mechanism is a loop of two or more factors that influences each factor in succession over time (Pruyt 2013). Since the aim of this study was to identify the feedback mechanisms that affect long-term functionality of rural water services, this research dealt solely with the qualitative system dynamics modeling process.

The creation of dynamic theory in the form of a CLD followed a three-phase process. In Phase 1, we identified the factors that can affect long-term water system functionality by conducting a systematic literature review. In Phase 2, distinctions were made regarding the *polarity of influence* (either a positive or negative influence) and *strength* between each factor identified in the literature with the help of a panel of water sector experts using both a *polarity analysis* and *cross impact analysis* (CIA), respectively. Lastly, Phase 3 identified and ranked dominant feedback mechanisms using the Phase 2 results from the CIA. Due to the multi-method approach employed for this research, we present the method, followed immediately by the results, for each phase below.

PHASE 1: FACTOR IDENTIFICATION

To identify the factors used in the CLD we performed a content analysis of journals published within the water sector using different combinations of the keywords “rural water”, “developing countries”, “sustainability”, “factors” and “indicators”. Scholarly articles were searched within the *Web of Knowledge* and *Engineering Village*, and non-scholarly articles were searched by direct referral from bibliographies. The process began by reading the abstract of each article found in the keyword search to ensure the research was related to rural water project sustainability in developing countries. Articles that did not meet this requirement were excluded. We coded and aggregated recurring references within the literature to factors that affected the sustained functionality of a rural water system in a developing country context. The coding process was performed within the qualitative data analysis software, QSR NVivo, chosen for its ability to easily allow researchers to code and manage qualitative data (Bazeley 2007). Finally, these coded factors were grouped within affiliated categories called "sustainability factors" to ensure the number of factors included in the CLD were of a manageable size, while covering the spectrum of key themes related to rural water service sustainability (Godet 1986; Scholz and Tietje 2002) .

The initial keyword search yielded 472 articles within scholarly journals and 176 non-scholarly articles found within the water sector. From these, 97 were chosen for their explicit identification of factors that influence long-term functionality of rural water services in developing countries. These 97 articles yielded 157 unique references to factors that potentially affect sustainability and functionality of a rural water system. These factors were then aggregated into "sustainability factor" affiliation categories, which included: *Government (Gov), Community (Com), External Support Management (Ext), Financial (Fin), Environment & Energy (E&E), Technology Construction & Materials (TCM), and Water System Functionality (WSF*). The factor "Water System Functionality" relates to how the water system is functioning at any particular time. For example, a water system that is not functioning properly might influence users' willingness to pay monthly tariffs, or could deplete funds available for system operation if excessive funds are continually used for system repair. Therefore, while the emergent outcome of interest in this study is the long-term functionality of rural water infrastructure, we deemed it necessary to create a factor based on water system functionality that could, in turn, influence other factors and thereby the overall long-term functionality of a water system.

Table 2-1 summarizes these sustainability factors, including a definition, the key sub-factors mentioned in the literature for each sustainability factor, and the number of articles that mentioned each sub-factor. The language used to define each factor was intentionally kept positive per best practices for causal loop diagramming (Sterman 2000). To this end, a common thread of these definitions was chosen as "the ability", where this "ability" relates to how the factor either enables or inhibits the objective of long-term water service functionality. Thus, as we progress into the identification of feedback mechanisms, it will be important for the reader to understand that these sustainability factors are thought to have a type of "capacity" or "ability" to, over time, increase or decrease in a way that influences overall project success (long-term functionality) or failure.

Table 2-1: Sustainability factors found in the content analysis

Sustainability Factor Category	Most Cited Sub-Factors	# of journal articles that cited factor	Definition
Government	Laws & Policy	21	The ability of the government to provide the necessary expertise and resources to help operate, maintain, monitor, and eventually replace the rural water system.
	Management	19	
	Governance	6	
Community	Participation	44	The ability and necessary demand present in a community to properly use, operate, monitor, maintain, and eventually replace the rural water system.
	Demand	30	
	Satisfaction	22	
External Support	Type of Support	15	The ability of an external organization or agency to provide the necessary expertise and resources to help operate, maintain, monitor, and eventually replace the rural water system.
	Cooperation	14	
	Post Const. Supp.	12	
Management	Maintenance	38	The ability of a water services management scheme to support the permanent and continually high functioning operation of a rural water system through proper operation, maintenance, and monitoring.
	Skilled Operator	29	
	Women Involvement	29	
Financial	Cost Recovery	48	The ability of water system management entity (community, external organization/ agency, and/or governing body) to financially support the costs associated with the operation, maintenance and eventual replacement of the rural water
	Financial Management	42	
	Cost of system or part	16	
Technology Construction & Materials	Spare Part Availability	31	The ability to obtain the appropriate technology, skilled labor, and spare parts to satisfactorily construct, operate and maintain a rural water system.
	Tech. Appropriateness	29	
	Construction Quality	9	
Environment & Energy	Resource	20	The ability of the available water resources to provide a continuously sufficient amount of clean water and the ability of the energy infrastructure, typically in the form of electricity, to support continual water system functionality.
	Source Protection	17	
	Energy Avail/Reliable	8	
Water System Functionality*	Quality	18	The quality of the water as it compares to the country
	Quantity	30	The quantity of water provided by the system as it compares
	Reliability	20	The duration of continuous operation of the water system
	Coverage	26	The availability of water services to users

* The water system functionality at a particular point in time, which may influence the other factors

PHASE 2: FACTOR INTERACTION

The purpose of Phase 2 was to identify the influence between factors. To accomplish this objective, we employed two complimentary methodologies, described below, to ascertain two distinct influence characteristics between sustainability factors. First, a polarity analysis was conducted using the input from water sector experts to characterize the dynamic influence (either direct or indirect) between factors. Second, a cross impact analysis (CIA) was employed using input from the same group of experts to characterize the strength between factors.

Polarity Analysis.

Using the factors identified in Phase 1, a Delphi panel of water sector experts was assembled in an attempt to reach consensus regarding the polarity of influence and associated model structure between the identified sustainability factors using expert assessments. The Delphi Method is a research technique to facilitate consensus within a group of experts regarding underlying relationships among causal factors (Vennix 1996; Linstone and Turoff 1975, Gratch 2012; Hsu and Sanford 2007). This is typically done through a multi-round survey whereby panelists are presented the aggregate group responses from the previous round in an attempt to facilitate consensus on a series of themes. Polarity of influence relates to the dynamic nature of pairwise influence between factors, where this influence can either be positive (an increase in one factor leads to an increase in the other) or negative (an increase in one factor leads to a decrease in the other). Identifying the pairwise polarity of influence between each of the factors provided the necessary building blocks for causal loop diagramming and the identification of feedback mechanisms (Phase 3).

A thoughtful selection of experts for the Delphi panel was considered critical to the quality of the study, as many researchers reference non-uniformity between panelist expertise as a major weakness of the methodology (Hsu and Sanford 2007). Thus, a 6-point criterion was used to select panelists, shown in Table 2-2, per recommendation of Hallowell et al. (2010). These criteria were created based upon the desire for panelist expertise and experience in rural water service sustainability in developing countries. To ensure a sufficient amount of panelists remained through the 2 rounds of this Delphi, we over-sampled and chose 23 panelists (Hsu and Sanford 2007; Ludwig 1997; Delbecq et al. 1975). Of these 23 panelists, 9 were consultants or advisors, 12 were directors, and 2 were academics, all focusing on sustainability of water systems in either Africa, Latin America or Asia. Panelists were given two weeks to respond to each round, an amount of time that is typically considered sufficient to allow panelists flexibility within the context of their schedules, yet short enough to have the study conducted in a reasonable timeframe (Delbecq et al. 1975).

Table 2-2: The criterion used to select the expert panel

Points[1]	Criteria
1 per article up to 3	Primary or secondary writer of scholarly journal articles on sustainable rural water services in developing countries
1 per article up to 2	Primary or secondary writer of non-scholarly journal articles on sustainable rural water services in developing countries
1	Member or chair of a nationally recognized committee focused on sustainable rural water services in developing countries
3	At least 5 years of professional experience doing international water aid as a director, practitioner, and/or policy maker
3	Conducts sustainable rural water service research for their job
2	Advanced degree in the field of engineering and/or international development
1	At least 5 years of experience living in a developing country
1	Has presented at conferences where the focus is on sustainable rural water service provision
[1]6 Points required for inclusion	

The Panelists were sent Qualtrics online survey questionnaires that asked them to indicate the influence of each sustainability factor on the other factors. Consensus between panelists for each influence was determined using a method known as the "Average Percentage Majority Opinion" (APMO). This was chosen as the preferred determinant for consensus as it was predicted that high levels of variability would exist in the overall agreement regarding influences between factors. APMO is an appropriate metric for general consensus in cases such as this, where panelist agreement is used as a viable indicator of consensus (Hwang 2004; Saldanha and Gray 2002; Cottam et al. 2004; Islam et al. 2006). Using APMO, each consensus limit between factors (i.e., Factor A on B, C, D…etc), was considered on a factor-by-factor basis. APMO had to be 51 percent, or greater, to be used as a limit for consensus, per the definition of majority (Gratch 2012). The equation for APMO is shown below.

$$APMO = \frac{\sum majority\ agreements + \sum majority\ disagreements}{Total\ Opinions\ Expressed}$$

In Round 1, the experts were acquainted with the objective of the study and given definitions for each of the factors, as shown in Table 2-1. Each expert was then asked to indicate the polarity of influence between the sustainability factors. For example, to obtain responses on the polarity between a particular factor—such as Factor A on Factor B—each expert was asked to select an option regarding how Factor A would influence Factor B, either: (+)—an increase in Factor A will cause an increase in Factor B; (0)—there is little or no influence between Factor A and Factor B or; (-)—an increase in Factor A will cause a decrease in Factor B.

The data from Round 1 were analyzed in Microsoft Excel using an individualized APMO consensus limit for each factor. Pairwise connections that met or exceeded this consensus limit of agreement were said to reach consensus, while connections that did not were passed on to Round 2. Consensus was reached on 27 of the 56 potential polarities of influence between the sustainability factors.

In Round 2, each panelist was asked to again make pairwise comparisons regarding the influence between the factors that did not reach consensus in Round 1 (29 influences). In this round, however, panelists were presented with the aggregated responses of the other panelists. Per Delphi protocol (Hallowell and Gambatese 2010), this was to see if a panelist reinterpreted the questions based upon the responses from the other panelists. Round 2 reached consensus on an additional 15 polarities, resulting in a total of 42 influences that reached consensus and 14 that did not. Influences that did not reach consensus were not included in the final CLD. For the 42 influences that reached consensus, 33 had positive polarity (+: direct relationships), 9 had no influence (0), and 0 had negative polarity (-: indirect relationship). This CLD, created using the consensus results on factor influence from Round 1 and 2 of the Delphi, is shown in Figure 2-1.

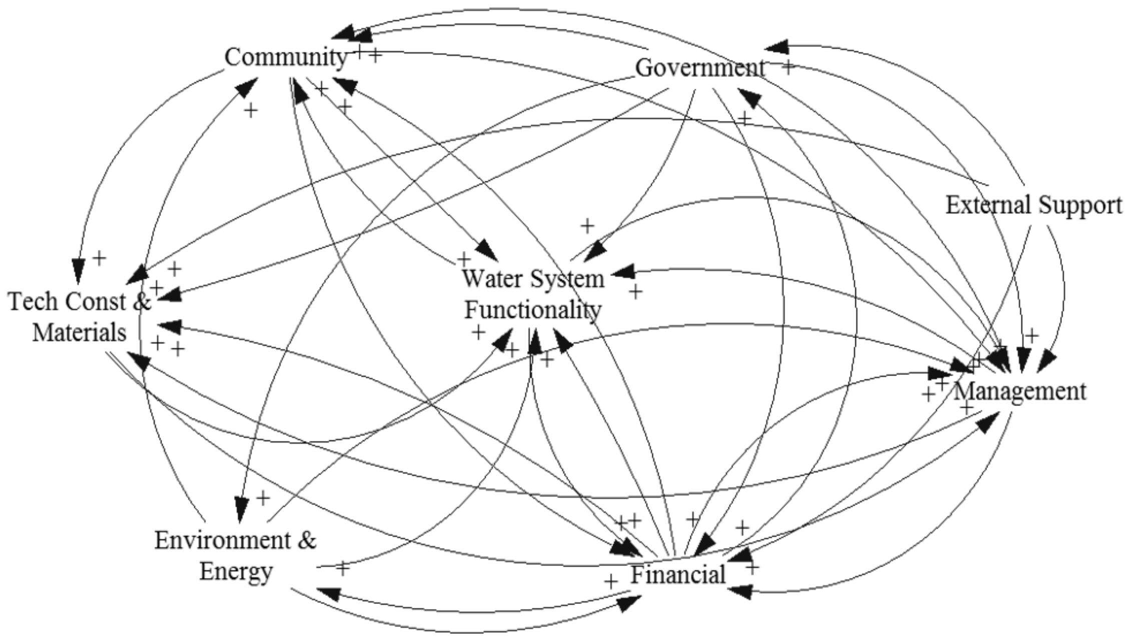

Figure 2-1: The CLD displaying factor influences that reached consensus from the expert panel

Factor Strength: Cross Impact Analysis (CIA).

An additional survey was conducted after the Delphi study with the same group of experts to obtain information regarding the causal strengths (versus only the polarity) between sustainability factors. Obtaining causal strengths would later allow for the quantitative identification of dominant feedback mechanisms within the CLD shown in Figure 2-1. This objective was accomplished using CIA. Performing a CIA entails systematically defining the strength between system factors through the creation of an "impact matrix" which organizes the pairwise interaction strength between these factors. To create this impact matrix, panelists were asked to indicate the causal strength between sustainability factors by filling out a 8 x 8 impact matrix, again within an online Qualtrics questionnaire. The causal strengths were indicated using the scoring scheme of non-existent (0), weak (1), medium (2), and strong (3) (Duperrin and Godet 1973; Torres and Olaya 2010; Julius 2002; Monto et al. 2005).

Expert responses on causal strengths had a wide range of variation. Because of this, these strengths were determined using the statistical mode of panelist responses for each of the 56 possible influences. The statistical mode was chosen as the appropriate measure of centrality due to the categorical nature of the data. Table 3 shows the impact matrix for each causal influence.

Table 2-3: Impact matrix from the expert survey showing the strength of influence between factors (row fators influence column factors)

	Gov	Com	Ext	Man	Fin	E&E	TCM	WSF
Gov	0	3	2	2	1	2	2	2
Com	2	0	1	2	2	1	1	2
Ext	2	2	0	2	2	1	2	2
Man	0	2	1	0	2	2	2	3
Fin	3	3	2	3	0	1	2	3
E&E	0	2	1	1	1	0	1	2
TCM	1	2	1	2	2	1	0	3
WSF	1	3	2	2	2	2	2	0

PHASE 3: FEEDBACK MECHANISMS

After polarity and strength between factors were identified from Phase 2, the CLD (Figure 2-1) was imported into the Ventana Systems Inc.'s VENSIM system dynamics modeling software (www.Vensim.com) to identify feedback mechanisms that influenced water system functionality using the program's "loop" tool. Specifically, the feedback mechanisms of interest were those that influenced the factor Water System Functionality. By considering feedback mechanisms that influenced this factor, we were able to directly infer how factors would influence water system functionality over time (i.e. long-term functionality). By combining interactions identified in the polarity analysis and CIA, it was then possible to identify 101 unique feedback mechanisms that influence the factor Water System Functionality.

The question then became: which of the 101 feedback mechanisms most influenced long-term water system functionality? To address this question, we identified dominant feedback mechanisms through factor influence ranking with the CIA data (Torres and Olaya 2010). Using the CIA impact matrix created in Phase 2, feedback mechanism strength was calculated by summing pairwise influence scores for each factor within each feedback mechanism. These feedback mechanism scores were normalized based on the number of factors within the loop to enable comparison. For example, the feedback mechanism WSF-Com-Fin-Man implies that water system functionality influences community involvement in the project, which then influences the funds available to operate and maintain the system, which then influences the capacity for the responsible managing entity to perform these duties of operation and maintenance, which thereby influences the water system functionality. This was scored as (3 + 2 + 3 + 3)/4 = 2.75 using influence strengths from the impact matrix (Table 2-3). The top-five scored feedback mechanisms with normalized scores of 2.4 and above, are shown in Table 2-4.

Table 2-4: Top-5 normalized ranked feedback mechanisms

Feedback Mechanism Description	Rank	Normalized Score
WSF-Com-Fin-Man	1	2.75
WSF-Fin-Man	2	2.67
WSF-Man-Fin	2	2.67
WSF-Com-Man	2	2.67
WSF-Com-Fin	2	2.67
WSF-Com-Fin-Man-TCM	3	2.6
WSF-Com-Fin-Gov-TCM	3	2.6
WSF-Com-Fin-TCM-Man	3	2.6
WSF-Fin-Gov-Com-Man	3	2.6
WSF-Com-Fin-Gov-Man	3	2.6
WSF-Man	4	2.5
WSF-Com	4	2.5
WSF-Fin	4	2.5
WSF-Fin-Com-Man	4	2.5
WSF-Fin-Gov-TCM	4	2.5
WSF-Fin-Gov-Man	4	2.5
WSF-Fin-Man-TCM	4	2.5
WSF-Fin-Gov-Com	4	2.5
WSF-Com-Man-TCM	4	2.5
WSF-Com-Fin-Gov	4	2.5
WSF-Fin-Gov-Com-TCM-Man	4	2.5
WSF-Com-Fin-Gov-Man-TCM	4	2.5
WSF-Com-Man-Fin-Gov-TCM	4	2.5
WSF-Com-Fin-Gov-TCM-Man	4	2.5
WSF-Man-Fin-Gov-Com	5	2.4
WSF-Fin-Gov-TCM-Man	5	2.4
WSF-Fin-Gov-Man-TCM	5	2.4
WSF-Fin-Com-Man-TCM	5	2.4
WSF-Fin-Gov-Com-TCM	5	2.4
WSF-Man-Fin-Gov-TCM	5	2.4
WSF-Com-Man-Fin-Gov	5	2.4
WSF-Com-Fin-Gov-E&E	5	2.4
WSF-Com-Man-Fin-TCM	5	2.4
WSF = Water System Functionality; Com = Community; Fin = Finances; Gov = Government; Man = Management; TCM = Technology, Construction & Materials; E&E = Environment & Energy		

DISCUSSION

Several findings may be inferred from the results of this study. From the polarity analysis, water experts in Rounds 1 and 2 of the Delphi indicated that all existing influences between factors were positive (+). This means the resulting feedback mechanisms are all reinforcing and would likely lead to a system behavior that is either one of growth (increasing), or decay (decreasing), depending on the dominance of the feedback mechanisms over time. In the context of a rural water system, a reinforcing feedback mechanism could imply water services that are increasing in functionality, or decreasing in functionality over time. An interesting example in the case of the former, a study by WaterAid Tanzania in (2009), observed a dramatic decrease in water system functionality over 2 to 7 years that seems to match this trend in functionality (WaterAid Tanzania 2009). The decreased water system functionality observed in the WaterAid study demonstrates the existence of one or more reinforcing feedback mechanisms similar to the inferred dynamic trend in water system functionality found in this study using the CLD (Figure 1). The complicated interactions between factors shown in the CLD also provide evidence of the complexity inherent in rural water project sustainability.

The 32 dominant feedback mechanisms from the CIA were found to contain six sustainability factors—Water System Functionality (WSF); Community (Com); Financial (Fin); Government (Gov); Technology, Construction, and Materials (TCM); and Management (Man)—as summarized in Table 4. Based on the methods used in this study, the most dominant feedback mechanism was Water System Functionality–Community–Financial–Management. With a methodological understanding that these four factors have an intrinsic “ability” or “capacity” to positively or negatively influence water system functionality—these findings imply that contexts where a water project has high levels of Community, Management, Financial “capacity”, are more likely to have long-term water system functionality. Conversely, any decrease in the capacity of any or all of these factors would seemingly lead to a cascading decrease in water system functionality over time, similar to what was seen in the aforementioned WaterAid Tanzania example.

The factors (WSF, Com, Fin, Man) that emerged in our results are well aligned with water sector literature, which suggest community involvement and effective financial and management schemes greatly influence the long-term functionality of rural water infrastructure in developing countries. Specifically, the literature mentions that a community's capacity to effectively engage with a rural water system is affected largely by the community's perceived need for a potable water system (thus creating a demand) and the community's involvement in the decision and selection process of the technological solution (Lockwood et al. 2003; Carter and Howsam 1999; Montgomery et al. 2009; Hopkins et al. 2004; Kleemeier 2000; Choguill 1996; Kaliba 2002; Prokopy 2005; Schweitzer and Mihelcic 2012). Additionally, there are many proponents for a framework that involves the community in managing the operation and maintenance of the water system (Sugden 2003; Lockwood et al. 2003; Montgomery et al. 2009; Jimenez and Perez-Foguet 2010). Conversely, many experts in the literature believes communities inherently lack the necessary capacity to manage a water project and suggest a model that heavily involves external institutional support by the government and organizations to provide guidance, legal frameworks and regulations for the proper operation and maintenance of a rural water system (Chatterley 2012; Shaw 2012). Existing research also critically analyzes existing management approaches as requiring a financial plan for recurrent cost recovery, typically in the form of monthly household tariffs, to fund the operation, maintenance and eventual overhaul of the water system (Abramson 2011; Kleemeier 2000; Davis 2014). However, the findings in this study take the factors identified in literature one step further by indicating their interaction as a dynamic chain of influence (feedback mechanism). This new representation of factor interaction is drastically different than what currently exists in literature because it not only lists important factors, but also shows how the systemic combination of these factors have the ability to continue influencing water system functionality over time, whether for the success or failure of the project.   A perspective situated at this level of understanding would enable practitioners to plan and implement holistic solutions and remedies to rural water issues in developing countries that are dynamic and systemic in nature.

The benefits of describing factor interaction as feedback mechanisms is exemplified well in a recent study by Davis (2014), which identified a similar influence between WSF-Com-Fin-Man for rural water projects in Central America. In their study, they found poor water services (WSF) often caused users to be less willing to pay their monthly user fees (Community – Finances), which, in turn, decreased the frequency and quality of training for the water committee members responsible to maintain the water system (Management), leading to a decline in system functionality (WSF) over time (i.e., WSF-Com-Fin-Man). In this case, the process-based theory presented a way for their team to articulate the systemic issues affecting water projects in Central America. The improved dynamic and structural understanding of the issue allowed them to prescribe an informed solution. They proposed empowering citizens to pay for their service, which would increase the ability of the water committee to maintain the system, and result in the provision of higher quality water services (Davis 2014).   This recent work by Davis (2014) demonstrates the impact an improved understanding of feedback mechanisms can have on strategic planning, and epitomizes the potential contribution our research has for the water sector by considering the dynamic interaction of factors that influence rural water project sustainability.

It is worth noting, however, that the top-ranked feedback mechanism (WSF–Com–Fin–Man) is only one of 31 other top-five ranked feedback mechanisms found in this study, many of which also included the factors: Gov and TCM (see Table 2-4). Certainly an argument can be made that any of these other feedback mechanisms could be equally, if not more important. For example, in a particular context the feedback mechanism WSF-Fin-Gov-Man, could conceivably be more dominant in a situation where the management (operation and maintenance) was instead the responsibility of the local government.   This provides an intriguing case for additional research efforts that elaborate on feedback mechanisms within different contexts (e.g., country, technology, management scheme, etc.). With the insight gained by these data, it may then be possible to learn more about the dynamic interaction of key factors that influence long-term functionality of future rural water projects.

Ultimately, there are intrinsic benefits to engaging in modeling of this type as a way to articulate the structuring of a problem (Alarcon and Ashley 1998). As Godet (1986) mentions, a systems modeling process can serve to foster "adaptive learning [as a way] to stimulate collective strategic planning and communications, to improve internal flexibility when confronting environmental uncertainty and to better be prepared for possible disruptions and adapt to choice of actions to the future context to which the consequences of the actions would relate" (p. 139). Similarly, the process of defining and describing a dynamic feedback mechanism offers a powerful means to hypothesize how a particular phenomenon unfolds over time (Richmond 2001). To that end, this research presents an initial framework for how future research of this type may be conducted using expert (or stakeholder) opinion for the production of knowledge and understanding on the feedback mechanisms that influence long-term functionality of rural water infrastructure. This could allow for an extension of sustainability frameworks for rural water project assessment, which are currently static, into a dynamic systems-based paradigm of decision making, using longitudinal case data in varying contexts. We believe that continuing to improve understanding on the dynamic interaction of factors that cause premature project failure will enable practitioners and policy makers to implement better-informed strategic plans for how rural water projects and programs provide communities with permanent access water services.

STUDY LIMITATIONS

As with any study, this research has limitations associated with the research methodologies employed. In the content analysis, the literature review, while systematic, was likely not fully exhaustive and may have left out potential causal factors in the coding process. Additionally, the process of aggregating factors into "sustainability factors" could have concealed those factors which were equally if not more important. Since the formation of factors into sustainability factors was a foundational element of this study, the errors which potentially exist in this process could significantly impact the validity of the study.

The Delphi expert panel also had potential for errors due to the limitations inherent in the methodology itself. For example, expert panelist consensus on factor influence yielded zero cases where an influence had negative polarity. There were many cases, however, where individual panelists found reason to indicate negative polarity given their own experiences and perspectives. Unfortunately, because the Delphi approach bases consensus on majority opinion, these important instances were not included in the final CLD. There were also instances where panelists conveyed the difficulty in generalizing rural water development from a "high level", and desired firmer contextual grounding from which to indicate the influences between factors. For example, of the 14 contested influences (influences that did not reach consensus), 5 were influences involving External Support, and another 5 were influences involving Environment & Energy. Regarding External Support, one panelist mentioned, "External support capacity can increase or decrease local government and community capacity, depending on the relationship. INGOs [International Non-Governmental Organizations] or private firms can be both helpful and/or harmful to the [government] and community management capacity…", and, "[If] external support refers to the private sector, I could be convinced that government capacity would have a positive influence, but on an NGO, generally in our experience here, the NGOs are influencing the government more than vice versa". Similarly, for the factor Environment & Energy, differences in opinion existed regarding the importance of influence. This difference in opinion is demonstrated by one panelist who stated, "environment is almost a [non-influential] variable, it depends just only the local environment". In contrast, another panelist wrote, "Environment & Energy are basic to a rural water system. If environmental conditions change, due to climate change, droughts, upstream withdrawals of water, etc., the rural water system may be affected if it does not have the capacity to absorb such changes". These examples, and many others, present the difficulties panelists had in responding to certain promptings on factor influence within the confines of a Delphi survey given the nuanced theme of rural water service sustainability in developing countries.

It may be possible to mitigate many of the aforementioned issues in future research through the use of fieldsite-based data and analysis to cross-compare the factor interaction indicated by experts. However, we believe our study demonstrates a novel and useful way to improve sector learning on rural water system sustainability using expert opinion.

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CHAPTER 3 – MANAGEMENT OF RURAL WATER SERVICES: A SYSTEMIC NETWORK APPROACH TO EVALUATING STAKEHOLDER ALIGNMENT

Keywords: *alignment; values; network; stakeholder; developing countries; rural water projects*

ABSTRACT

Water sector literature attributes a substantial cause of rural water system failure in developing countries to poor alignment between project stakeholders. This study aimed to investigate a means for assessing stakeholder alignment by comparing the systemic interaction of stakeholder values, where the term "stakeholder values" refers to aspects stakeholders believe are necessary to ensure rural water services are sustainable. The research held focus groups with key stakeholder groups involved in the management of rural water infrastructure in Terrabona, Nicaragua to identify stakeholder values, and then used cross impact analysis to evaluate how these values interacted to form stakeholder value networks (SVN). Using ranked and normalized betweenness centrality measures, the structures of SVNs were compared to determine alignment. Results from this study showed high levels of stakeholder alignment on the topic of finances for the sustainability of water systems, while there was marked non-alignment regarding the involvement of local government and organizations in the management of water infrastructure. This study offers compelling evidence for future studies to assess stakeholder alignment by identifying and structurally analyzing stakeholder value networks.

INTRODUCTION

Significant progress has been made in improving access to potable water in developing countries over the past decade (JMP 2014); however, studies have shown that substantial issues with project sustainability exist in spite of these accomplishments (JMP 2014; Sustainability Charter 2014; Davis 2014). One important component for project sustainability is the unified coordination or *alignment* between key stakeholder groups (Lockwood et al. 2003; Lockwood and Smits 2011; RWSN 2010). Unfortunately, water sector literature often blames incongruous alignment between donors, country-level organizations and governments for confounding sustainability (IRC 2012; WaterAid 2011; Williamson et al. 2008; Ferguson 2001). For example, the IRC 2012 tells of their experience with a "vicious cycle" that results when the lack of stakeholder coordination causes nonalignment within sector policy, which, in turn, causes weakened stakeholder collaboration and unsustainable water services. In addition, Jansz (2011) mentions that, in spite of the many factors that can influence long-term sustainability of water infrastructure, it is paramount that stakeholders work together effectively with transparent coordination. Similarly, Pearce-oroz et al. (2011) argues that "inter-sector coordination contributes to sustainable water services, and closer alignment between local and national stakeholders"(p.6) are critical for this end goal of sustainability.

Effective coordination and alignment between stakeholders, as a key element for water project sustainability, comes as no surprise. Project management literature clearly indicates that stakeholder alignment is imperative for long-term project success (Freeman 1984, 2001; Loucopoulos and Kavakli 1995; Vaidya and Mayer 2014). This literature mentions that alignment is fostered and realized through the agreement between stakeholder values and goals, which drive and unify stakeholder actions that are beneficial to project success (Winn 2001; Luftman 2003). Thus, in accordance with the aforementioned literature, this research posits that the emergent outcomes from stakeholders' *values* – as they relate to the ideal management of rural water infrastructure –are their associated *actions*. Therefore, specifically evaluating certain aspects of stakeholder values would intuitively enable an improved ability to judge how stakeholders will align their actions towards the end goal of long-lasting water services (Rokeach 1973; Keely 1983; Zang et al. 2008). As such, the aim of this research was to gain understanding of stakeholder alignment through the emergence and analysis of their respective values, and how these values interact.

This study proposes a method for comparing stakeholder values through the creation and analysis of stakeholder value networks (SVN). We elected to use *stakeholder theory* and *network theory* to provide a theoretical basis for these proposed methods of data collection and analysis. Stakeholder theory suggests that mapping stakeholder values as they relate to a particular end goal (in this case, the long-term functionality of rural water infrastructure) can enable an improved understanding of their future actions (Winn 2001**;** Weiner 1988; Freeman 2001; Mills et al. 2009; Rosenblueth et al. 1943). Similarly, network theory suggests that the structural interaction of these stakeholder values – shown by drawing a network comprised of nodes (in our case stakeholder values) and lines/edges that connect these nodes (to show the interaction between these values) – can provide insight into the type of stakeholders' actions that potentially manifest (Wasserman and Fraust 1994; Freeman 1979; Scott 2000; Borgatti and Everett 2006; Wossen et al. 2013).

As a proxy for stakeholder alignment, this research proposes to assess stakeholder action by comparing the structural interaction of their values networks. First, we propose using stakeholder theory for the illumination of stakeholder values based on their goals for water project success. Second, we propose using network theory as a basis for the use of SVNs to display a meaningful interaction between stakeholder values. Lastly, we combine these two theories to develop a proxy for alignment based on stakeholder action inferred through the structural analysis of their value networks. Figure 3-1 summarizes the synthesis of these two theories that guided our research methods.

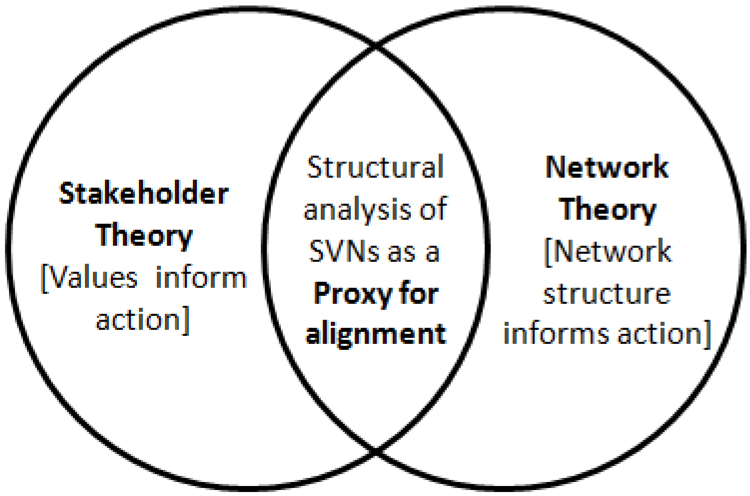

Figure 3-1: Theory synthesis

As a result, this research addresses the following questions within the context of rural water projects in Terrabona: *What are the values of stakeholder groups involved in the management of rural water infrastructure in Terrabona, Nicaragua? How are these values structurally connected as a network? How do each stakeholder group's value networks differ? What can these differences tell us about their alignment towards the end-goal of long-lasting water services?* By using this approach, the interaction of stakeholder values within value networks is elucidated and compared structurally to illuminate alignment.

METHODS

The multi-phase research approach employed for this study collected data from focus groups with four rural water project stakeholder groups in the municipality of Terrabona, Nicaragua. These focus groups helped us explore, identify and link stakeholder group values as they relate to the idealized management of rural water projects. These stakeholder values were qualitatively coded to identify recurring themes in stakeholders' language as a way to aggregate values into SVNs. We constructed SVNs for each of these stakeholder groups by performing a structural cross impact analysis within each focus group. We then compared and contrasted the structural differences between SVNs using betweenness centrality scores to highlight stakeholder alignment (or non-alignment). The methodological phases, as they relate to data collection and data analysis, are explained below.

DATA COLLECTION

Focus groups were conducted in Terrabona, Nicaragua. Terrabona was chosen as the research site due to the diverse spectrum of stakeholders involved in rural water infrastructure and the associated large number of water projects – many of them functioning sub-optimally (El Porvenir 2013). Terrabona is located 40 miles north of Managua, Nicaragua, the country's capital, and has a population of 13,000, primarily located in 61 separate rural communities. Over the past 15 years numerous water projects have been installed in Terrabona by the local government, and non-profit organizations, providing coverage of 77% (about 47 projects); however, of these 47 projects, only 54% are functioning properly (El Porvenir 2013).

We used focus groups to identify and map stakeholder values. Focus groups were used because of their ability to effectively bring to the surface stakeholder beliefs, perceptions and language (Stewart 2014). These focus groups involved stakeholders within the municipal government (specifically government officials responsible for rural water infrastructure implementation and management in Terrabona), local water committees, a local non-governmental organization (NGO), and students and faculty within a local academic institute. These stakeholder groups were chosen because of their direct and indirect involvement with rural water project implementation and water system management in Terrabona. Students and faculty chosen to participate in the focus groups were specifically those teaching or taking classes related to rural water management. While these students and faculty were not directly involved in water project implementation or water system management, we chose to include this group because many of these students would later be employed by the municipal government as government officials involved with water infrastructure planning in Terrabona.

Focus groups were conducted individually for each group of stakeholders to avoid conflicts or biases between different stakeholder groups. Audio was recorded for each focus group session to aid in the subsequent step of value aggregation and comparison. Table 3-1 displays some basic information regarding each focus group session and displays each stakeholder group's respective involvement with rural water infrastructure.

It may be seen in Table 3-1 that the Water Committees and Academics stakeholder groups were considerably larger than the other two groups. For these larger focus groups, a significant effort by the focus group facilitator went into ensuring each stakeholder was involved in the discussion. The process of facilitating a discussion with a larger number of focus groups participants resulted in sessions that were approximately one hour longer for both the Water Committees and Academics stakeholder groups.

Table 3-1: Focus group information

Stakeholder	Involvement with Water Service	# of Participants	Length (hr)
Government	Implementation, management, training	5	2
Organization	Implementation, management, training	6	2.5
Water Committees	Management	14	3
Academics (students and faculty)	Best practices, education of future government-based practitioners	16	3

Focus group sessions began by asking stakeholders the open-ended question: *"what do you feel are the most important things that lead to the long-term functioning of a rural water system?"* The wording of this question effectively asked stakeholders to provide "things" (values) they thought might lead to the end goal of long-term water system functionality. Each stakeholder group was then given time to brainstorm, discuss, and reach consensus on the most important values.

Once these stakeholder values were identified and aggregated into subgroups, the next step was to ascertain the influence between values that would later be used to build each SVN. To do this, stakeholders were prompted to systematically identify *"the interaction between each value"*, through pairwise connections (i.e., the influence of good accounting on community participation, good accounting on proper system maintenance, community participation on good accounting, etc.). This method of pairwise interaction was considered a systematic, simple, and objective way to find the influence from one stakeholder value on the other (Turnstone 1927; Bradley 1954; Linstone and Turoff 1975; Saaty 2008; Cheung et al. 2010; Gregory and Wellman 2001). Practically, this process entailed eliciting and writing down all possible pairwise interactions. The focus group session ended after each pairwise influence was discussed, resulting in a synthesized list of pairwise comparisons between stakeholder values for each stakeholder group.

DATA ANALYSIS

Each focus group session was recorded, transcribed in Spanish, and then imported and qualitatively analyzed in QSR NVivo 10 software to code similarities and differences between the stakeholders' language (QSR International Pty Ltd. 2012). Transcriptions were intentionally kept in Spanish to preserve many of the contextual subtleties available only in the native tongue of focus group participants. Similar stakeholder value names that were described with similar language (wording) by stakeholders were then put into generalized categories, which enabled the comparison of these values between each of the stakeholder groups. Specifically, the recurring language used by stakeholders to describe the important values for long-term functionality of water infrastructure was used to create these means for stakeholder value generalization.

With the list of generalized stakeholder values, it was then possible to create a SVN for reach stakeholder group. SVNs were built using the value interactions (the second part of each focus group session) indicated by the stakeholders. Interactions between the stakeholder values allowed us to build SVNs using R-Project for Statistical Computing (R-Project 2015), where each SVN displayed the mapped interaction between stakeholder values. To structurally compare SVNs, this research used *betweenness* *centrality* as it allowed the research team to evaluate the position of key values within the network with respect to other values, and specifically the extent to which a stakeholder group's values connect other values and act as a "bridge" within the system along the shortest path, known as the "geodesic". (Freeman 1979; Scott 2000; Borgatti 2005, Hanneman 2001). An example illustrating betweenness is shown in Figure 3-2. In this figure, the node with the highest betweenness score would be C, because it bridges (or controls network-wide connections) between nearly all of the nodes.

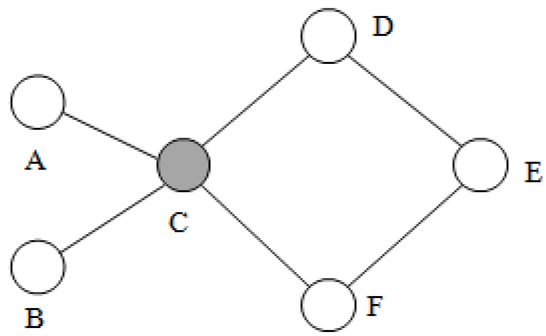

Figure 3-2: Betweenness illustration (the shaded node (C) has the highest betweenness score)

All centrality techniques implicitly measure the effect network structure (relationship between nodes) has on a particular outcome. An example effect could be how money is transferred, how people communicate, or how packages are delivered (Borgatti 2005). In this study, we assume the structural interaction between values affects stakeholders' decisions and subsequent actions, thereby affecting how they align their efforts.

Calculation of betweenness scores was accomplished by creating a SVN for each stakeholder group using the open source R-package "statnet" (Acton and Jasney 2012). The betweenness scores for each SVN were then normalized to allow comparison between the four stakeholder groups. The equation we used to calculate these normalized betweenness scores is shown below:

$$g(v) = \frac{\sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}}}{(N-1)(N-2)/2}$$

Where:

$g(v)$ = the normalized betweenness centrality score for a particular value
v = the value of interest
σ_{st} = the total number of shortest paths that pass between value s and value t
$\sigma_{st}(v)$ = the number of those shortest paths that pass through value v
$N =$ the total number of values in the SVN

Normalized betweenness scores were calculated for each value within each SVN, and these scores were ranked from high to low to allow a basis for comparison. We assessed alignment between stakeholders by comparing the absolute difference between betweenness scores using three different scoring metrics: *local*, *value-based* and *stakeholder-based* alignment. These three scoring metrics were created to make important distinctions between different forms of stakeholder alignment. For example, local alignment describes alignment that exists between two stakeholder groups (i.e., Academics with Organization (Aca:Org)) over a single stakeholder value. A local alignment score is calculated as the absolute difference in normalized betweenness scores for a particular stakeholder value between two stakeholder groups. Value-based alignment shows the level of alignment that exists between all the stakeholders for a certain stakeholder value, considering all 6 possible paired stakeholder comparisons (i.e., Academics with Government (Aca:Gov), Academics with Organization (Aca:Org), Water Committee with Academics (WC:Aca), etc.). As such, a value-based alignment score is calculated as the mathematical sum of all local alignment scores available for each individual stakeholder value. Lastly, stakeholder-based alignment describes alignment that exists for a particular pairing of stakeholder groups considering all stakeholder values. A stakeholder-based alignment score is calculated as the mathematical sum of all possible local alignment scores shared between two stakeholder groups for all the stakeholder values. Because in some cases local alignment scores could not be calculated, we normalized value-based and stakeholder-based alignment scores to allow comparison. In the next section we present further examples for how these metrics were calculated.

RESULTS AND DISCUSSION

This section first presents the results from the focus groups and then the network analyses. Normalized betweenness scores for each stakeholder group and structural differences between each SVN are compared and discussed using the aforementioned alignment metrics in conjunction with quotes (translated from Spanish to English) from focus group participants and observations from the field. In this section, we highlight either alignment or non-alignment based on these findings and analysis methods.

VALUE GENERALIZATION

The focus group activities yielded a spectrum of stakeholder values for each group. These values were aggregated into 11 values that, at minimum, 2 out of 4 stakeholder groups shared. Using these criteria, it was possible to cover the majority of values mentioned by the stakeholders, while permitting comparison between at least two stakeholders. However, Table 3-2 shows that the majority of stakeholder values were shared between 2 and 3 stakeholder groups – a result that required us to normalize our scoring metrics. The stakeholder values that emerged through this selection process were: Technology (Tech), Management (Man), Communication (Com1), Community (Com2), Infrastructure (Infra.), Government & Politics (G&P), Water Resources (WR), Water System Functionality (WSF), External Support (Ext.), Finances (Fin), and Training & Education (T&E). Table 3-2 displays a description of each generalized stakeholder value, along with the language and context used by the stakeholder groups.

Table 3-2: Value context by stakeholder

Value	Stakeholder	Context Referenced
Technology	Organization	Quality of construction and materials so the system works properly
	Academics	
	Water Committees	The type of system being implemented as it influences
Management	Organization	Management would be organized, and all stakeholders would collaborate with effective leadership over the life of the project
	Water Committees	Ownership is taken by the water committees who would organize effectively and frequently to assess and maintain the
	Government	Management of the water system should be provided by the water committees with support from the local government
Community	Organization	Necessity, demand, motivation, priority, drive community member interaction with the water system
	Academics Organization	A willingness to pay, and a need for a culture of payment within the community; level of community education
Infrastructure	Government	Transportation infrastructure and reliable affordable energy (if applicable)
	Academics	
	Organization	
Government & Politics	Government	Government continuity, communication, law establishment and reinforcement for water committees
	Water Committees	
	Academics	
	Organization	Tariff regulation
		Regulation of the water system technology
Water Resources	Water Committees	Climate change, natural disasters, deforestation, land use, and source protection
	Government	
	Academics	
	Organization	Water levels, conservation, availability of water resources
Water System Functionality	Water Committees	A functioning system (water quality, quantity and continuity) is critical for the satisfaction of the community who ultimately pay for the service.
	Government	
	Academics	
	Water Committee	
External Support	Government	Visits from an organization
	Academics	Organizational involvement, visitations, trainings
	Organization	The organization picks technology, and continually manages the
Finances	Government	Available funds saved to perform operation and maintenance of system available through the collection of monthly user tariffs
	Academics	
	Water Committees	
		Economic level of people
	Government	Financial reporting to community
Communication	Water Committees	Communication related to information on water system functionality, issues, etc.
	Water Committees	
Training & Education	Academics	Trainings of users on proper and responsible use of the
	Government	Training regarding water committee laws and the operation and maintenance of the system
	Organization	

NETWORK ANALYSIS

The resulting SVNs for each stakeholder group are shown below in Figure 3-3 as a way to visualize the structural interaction of stakeholder values. In these network diagrams each node is a stakeholder value, and each line is an interaction between these values. Arrows indicate the direction of influence of one value on the other. For example, T&E → WR means Training & Education affects, and thus informs decisions, related to Water Resources. The associated normalized betweenness scores are shown below for each SVN in Table 3. Because our criteria for stakeholder value generalization allowed a minimum of two stakeholder group pairings, many of the stakeholder values were not comparable over all the stakeholder groups. In this case, stakeholder values that were not unanimously mentioned in a focus group session for a particular stakeholder group are designated with “no data”. Normalized betweenness scores of zero denote stakeholder values that are structurally unimportant; that is, they were not structurally necessary to bridge between other stakeholder values.

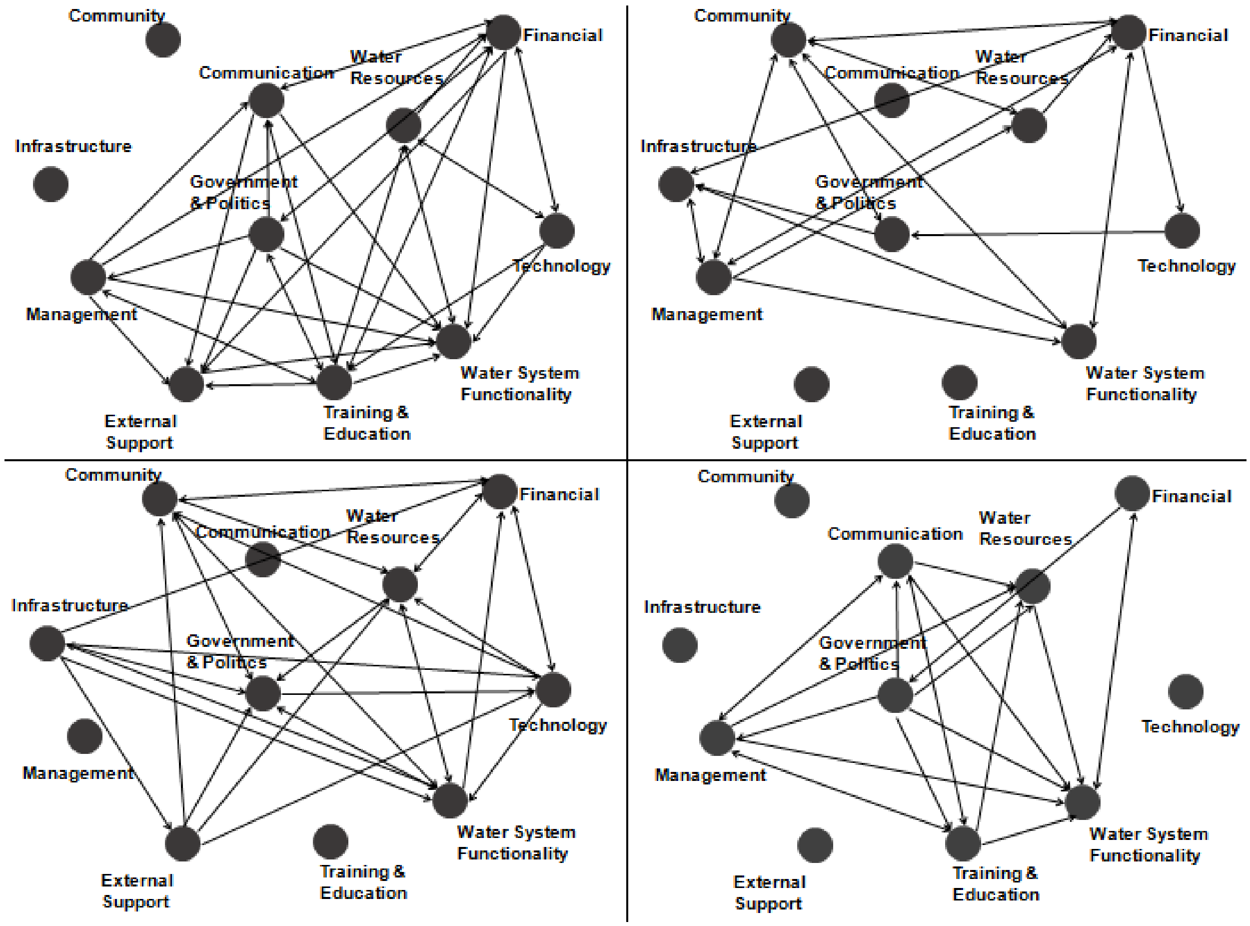

Figure 3-3: Stakeholder value networks, Community (top left), Organization (top right), Academics (bottom left), Government (bottom right), G&P = Government & Politics, Man = Management, T&E = Training & Education, Com1 = Communication, WSF = Water System Functionality, WR = Water Resources, Fin = Finances, Ext = External Support, Tech = Technology, Infra = Infrastructure, Com2 = Community.

Table 3-3: Normalized betweenness scores for each stakeholder group ordered from highest to lowest

Water Committees		Organization		Government		Academics	
T&E	0.3170	Fin	0.3373	WSF	0.4000	G&P	0.2937
Fin	0.2917	Com2	0.2103	Fin	0.4000	Fin	0.1258
WSF	0.2277	Tech	0.1429	G&P	0.3667	WR	0.1190
Tech	0.0714	G&P	0.1429	Man	0	WSF	0.0722
Man	0.0104	Man	0.1032	WR	0	Tech	0.0425
G&P	0.0104	Infra	0.0675	Com1	0	Com2	0.0425
WR	0	WSF	0.0198	T&E	0	Ext	0.0107
Com1	0	WR	0.0000	Tech	No data	Infra	0.0079
Ext	0	Com1	No data	Com2	No data	Man	No data
Infra	No data	T&E	No data	Infra	No data	Com1	No data
Com2	No data	Ext	No data	Ext.	No data	T&E	No data

ALIGNMENT COMPARISON

Local, value-based, and stakeholder-based alignment scores were calculated using the normalized betweenness scores in Table 3, and are shown below in Table 4. In Table 4, all cells (apart from cells on the far right column and bottom row) display a local alignment score for a particular stakeholder value, calculated as the absolute difference in stakeholder value betweenness scores between two stakeholders. For example, the local alignment score for the Finances stakeholder value compared between the Water Committees and Organization (WC:Org) stakeholder groups is calculated as 0.2917 (WC) – 0.3373 (Org) = 0.0456. The cells in the far right column named "Norm row sum", display the normalized value-based alignment scores, calculated by summing all local alignment scores available in each row and dividing by the number of alignment scores for a particular value. As mentioned previously, we chose to normalize this score because in some cases local alignment scores could not be calculated (denoted as "no data" in Table 3-3 and Table 3-4). In other words, normalizing the row enabled comparison of value-based alignment calculation for cases where localized alignment scores did not exist. For cases where only one local alignment score existed in a particular row, a value based alignment score was deemed redundant and not calculated (i.e., for Communication, Training & Education and Community stakeholder values). A similar normalizing process took place for stakeholder-based alignment, where in this case, summing was of cells in a particular column (Norm. Column Sum).

Table 3-4: Alignment scores for the three alignment metrics (lower numbers denote alignment)

Value	WC:Org Org:WC	WC:Gov Gov:WC	WC:Aca Aca:WC	Org:Gov Gov:Org	Org:Aca Aca:Org	Gov:Aca Aca:Gov	Norm. Row Sum
Finances	0.0456	0.1083	0.1659	0.0627	0.2115	0.2742	0.1447
Gov & Politics	0.1325	0.3563	0.2833	0.2238	0.1508	0.0730	0.2033
Management	0.0928	0.0104	no data	0.1032	no data	no data	0.0688
Water Resources	0	0	0.1190	0	0.1190	0.119	0.0595
Wat Sys. Funct.	0.2079	0.1723	0.1555	0.3802	0.0524	0.3278	0.2160
Technology	0.0715	no data	0.0289	no data	0.1004	no data	0.0669
Communication	no data	0	no data	no data	no data	no data	--
Training and Edu.	no data	0.317	no data	no data	no data	no data	--
Community	no data	no data	no data	no data	0.1678	no data	--
Infrastructure	no data	no data	no data	no data	0.0596	no data	--
Ext. Support	no data	no data	0.0107	no data	no data	no data	--
Norm. Column Sum	0.0917	0.1378	0.15052	0.1540	0.1231	0.1985	
	Stakeholder-based Alignment						**Value-based Alignment**

Comparing local, value-based, and stakeholder-based alignment scores highlights interesting findings on stakeholder alignment in Terrabona. Low scores for each of these metrics imply alignment, and conversely, high scores imply nonalignment. We now present the results from these quantitative analyses for alignment and nonalignment in conjunction with quotes from participants and contextual support from our observations in the field.

Alignment

The Water Resources stakeholder value appeared to have the lowest value-based alignment score (0.0595), meaning consistently low local alignment scores for each stakeholder pairing, and good alignment for the value overall. Interestingly, the only SVN that yielded a normalized betweenness score over null for Water Resources was for the Academics stakeholder group. The Academics local alignment score of 0.119 for Water Resources (as opposed to 0 for the other stakeholders) is supported by a quote from an Academics stakeholder who stated: "*If water resources are not managed well, the* *water system will not be sustainable".* While the other stakeholders mentioned the importance of water resources for water system sustainability, this importance did not emerge based on their SVNs.

Additionally, both Management and Technology stakeholder values received low value-based alignment scores (0.0688 and 0.0669, respectively). Within each focus group session, the majority of stakeholders agreed on the value of Management as the responsibility of the Water Committees (a management scheme known as "Community Based Management"). However, the details on how management was to be executed within water committees varied substantially between stakeholder groups. As is shown in Table 3-1, the Water Committees stakeholders believed they were in charge of the water system; however, Organization stakeholders believed the water committee was the primary maintainer of the system, but that all stakeholders should be involved; and Government stakeholders believed the community should be in charge of managing the system, with the help of the government. These apparent disparities in perception of the ideal management schemes are reinforced further in the network diagram (Figure 3-3 top left), which shows a high level of influence from Management on other stakeholder values, yet a low level of influence from the other stakeholder values towards Management. This shows that Management has a greater affect on other stakeholder values than vice versa; and thus the low betweenness scores for Management overall.

The Technology stakeholder value had a moderately high normalized betweenness score between the stakeholder groups and was referenced primarily in terms of issues related to electricity costs, shown by a quote from one Organization stakeholder:*"The type of system is important, because there are systems that pump by gravity and some systems that pump by electricity. The water committee needs to be careful with water systems that pump by electricity, because they need to understand the costs associated with this type of technology, and know that if they don't pay their electricity bills, the electricity will be cut-off, and water will stop flowing."* The network diagrams in Figure 3-3 support this quote for all three stakeholder groups who mention technology (WC, Aca and

Org); where the structural interaction between these stakeholder values implies that Finances affects Technology, indicating that Finances for operation and maintenance must be considered before choosing a technology.   This is representative of the high level of alignment between these three stakeholder groups regarding the Technology stakeholder value.

Finances, despite receiving a moderately high value-based alignment score of 0.1447, consistently earned the top-two normalized betweenness scores for all stakeholder groups (Table 3-3), meaning Finances was a hub for connection to other stakeholder values. Evidence of the influence of Finances on other stakeholder values was seen in conversation between stakeholders during the focus groups, as they discuss about how Finances affects other aspects of water system management; thereby supporting the consistently high betweenness scores seen for Finances. The language used by water committee stakeholder groups presents a telling example of this connectivity for Finances to Management, Technology, Government and Water Resources stakeholder values, summarized in Table 3-5.

Table 3-5: Connectivity of the Finances stakeholder value stated by the Water Committee stakeholder group

Linked Value	Quote
Management	*“If the finances are managed well, people have faith in their water committees and then they’ll pay* [monthly tariffs].”
Technology	“*The type of technology used affects the amount users have to pay.”*
Government	*“If we have lots of money, we don’t have to depend on the government,[and] if we’re sustainable, we wouldn’t depend on them…well at least not 100%.”*
Water Resources	*“If there was more funds* [in the community overall], *there could be more reforestation… and if there was more money, than less people would be cutting down trees* [for fires]*, which would affect the environment.”*

Of the six potential stakeholder-based alignment comparisons (considering all stakeholder values), the lowest scoring comparison was Com:Org (0.0917). That alignment appears to exist between this stakeholder pairing agrees with what we observed in Terrabona. The Organization stakeholder group was observed to be closely involved in education and training programs of the Water Committees, and stated that an important aspect for a successful water project was the motivation and empowerment of water committee members to properly manage their water system. This alignment is demonstrated quantitatively by their local alignment score (WC:Org) of 0.0928 for Management, and a relatively high normalized betweenness score of 0.2103 for the Community stakeholder value. This high betweenness score is further supported by various Organization stakeholder quotes that mention the importance of the Community for the sustainability of the water project, outlined in Table 3-6:

Table 3-6: Connectivity of the Community stakeholder value stated by the Organization stakeholder group

Linked Value	**Quote**
Maintenance	"[water committees] *will do the maintenance, if they are motivated*."
Finances	"*If a culture is made around gathering funds and saving, this will affect the ability to have funds for maintenance. If there isn't a culture of paying, the people won't pay*.
External Support	"*If the community is motivated, they will search out donors*."
Community	"*Without empowerment and motivation, you can't have a sustainable project*."

<u>*Non-Alignment*</u>

Government & Politics and Water System Functionality stakeholder values appeared to have the highest local (0.3563 and 0.3802, respectively) and value-based alignment scores (0.2033 and 0.2160, respectively), thus signifying an apparent lack of alignment with these two stakeholder values. Government & Politics is an easy target, since the majority of stakeholders had strong opinions regarding how the government should be involved with rural water supply. This is illustrated well by the quote from a Water Committees stakeholder about not wanting to depend on the government, shown in Table 3-5: *"If we have lots of money, we don't have to depend on the government,* [and] *if we're sustainable, we wouldn't depend on them…well at least not 100%."* This stands in obvious contrast with how the Government stakeholder group desires to interact with community water committees by offering them incentives if they agreed to be officially legalized by the government, a process that takes some water committee years to complete: *"So the community will have a water* *system that works well, the community needs to organize a water committee. We organize the meetings, and we explain the water rights, and we help them do the paper work to become officially recognized so they may have energy subsidies and bank accounts. The government helps improve the capacity of the water committees to support the water system".*

The Academics stakeholder group SVN indicated the high importance of government involvement for sustainable rural water services, receiving a normalized betweenness score of 0.2937 for Government & Politics (G&P). This high normalized betweenness score for G&P indicates a high connectivity between G&P and the other stakeholder values, as supported by the one Academics stakeholder's quote: "*Whether the water system is functioning isn't based on the government, the government isn't involved much in the maintenance. They influence everything else.*" Strangely, the Government and Academics stakeholder groups (Gov:Aca) appeared to be the most poorly aligned, with the highest stakeholder-based alignment score of 0.1985, largely driven by their high local alignment scores for Finances (0.2742) and Water System Functionality (0.3278). Similarly, the Organization and Government stakeholder groups (Org:Gov) also appear out of alignment, receiving the second highest stakeholder-based alignment score of 0.1540.

STUDY IMPLICATIONS AND LIMITATIONS

The findings from the structural analyses of SVNs showed alignment existed between the Water Committee and Organization stakeholder groups – likely due to how these two stakeholder groups work together and communicate. Alignment between stakeholder groups regarding each individual stakeholder value existed for the values: Management, Technology and Finances. For the stakeholder value, Management, this related to the importance of a viable community based management scheme; for the Technology stakeholder value, this related to the importance of selecting an appropriate technology that could be feasibly maintained by the water committee; and for Finances, this related to the importance of available funds for the operation and maintenance of the water system. That alignment exists based on the structural interaction of these stakeholder values implies similar decisions would be made by stakeholders related to a project's finances, management, and technology. This connection between stakeholder value interaction and alignment is supported by the observed management decisions made in Terrabona regarding appropriate technology based on regional finances and the costs of operation and maintenance.

The largest discrepancy of stakeholder-based alignment was found between the Academics, Organization and Government stakeholder groups. Alignment could be bolstered through improved communication between these stakeholder groups to enable an alignment of their respective water management plans. Improved alignment between these stakeholder groups might then lead to improvements in how community based water system management schemes are successfully planned, implemented and managed in Terrabona with the help of external support from the government and local organizations – a strategy that is in-line with current best-practices in the water sector (Lockwood et al. 2003; Smits et al., 2012; Pushpangadan and Gangadhara 2008; Montgomery et al. 2009; Prokopy et al. 2008; Davis et al. 2008; IRC 2013).

The presentation of qualitative examples gathered from the focus groups allowed us to support the quantitative findings on stakeholder alignment based on the structural analysis of SVNs. As such, this study demonstrates a novel and useful way to quantitatively evaluate stakeholder alignment. However, it remains to be seen whether comparing stakeholder value interaction accurately predicts future stakeholder alignment, as well as the resulting impact varying levels of alignment may have on water service sustainability. Thus, further research will be needed to validate these and any subsequent findings by investigating if stakeholder alignment or nonalignment truly manifests in the way inferred by their value networks; and if this improved alignment truly leads to sustainable water services.

Finally, it is important to note that a stakeholder group representing water users was not included in this study because of our limited research resources. As a result of these constraints, we deemed it infeasible to obtain a representative sample of water user opinions within a single focus group while maintaining the focus group size used for the other four focus groups (i.e., less than 16 participants). Although most of the Water Committees stakeholders in this study were water users themselves, future studies would certainly benefit from the emergence and analysis of stakeholder values from water users, potentially through a series of focus groups conducted within multiple communities.

CONCLUSIONS

This study demonstrates a way to evaluate stakeholder alignment through the analysis of stakeholder value networks (SVN). SVNs were created using data gathered in focus groups with four different stakeholder groups (Government, Water Committees, Academics and Organization) involved in rural water infrastructure implementation and management in Terrabona, Nicaragua. Using data gathered in these focus groups in conjunction with qualitative coding, we identified 11 stakeholder values that could be compared between at least two of the four stakeholder groups. By comparing pairwise interaction between stakeholder values within focus groups, we then created and structurally analyzed SVNs using betweenness centrality as a means to judge stakeholder alignment.

The methods employed in this study allowed for insightful stakeholder alignment comparisons to emerge. From these insights, it was possible to highlight alignment (and nonalignment) of stakeholders based on the structural interaction of their values, which thereby aided in developing recommendations for ways to improve stakeholder alignment in Terrabona. For example, the apparent lack of alignment between Government and Organization stakeholder groups informed our recommendation for the improved communication between the Government and Organization stakeholders to better support existing community based management schemes in Terrabona. This same level of insight on stakeholder alignment in Terrabona could likely be gained by applying this method in other areas and contexts by water practitioners (local organizations, NGOs, etc.) and academic researchers interested in making recommendations for improved stakeholder alignment. Thus, this study provides ample motivation for future research that continues to grow understanding on stakeholder alignment by comparing true stakeholder alignment outcomes with the alignment assessments found by the structural analysis of stakeholder value networks.

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CHAPTER 4 – STRATEGIC PLANNING OF RURAL WATER DEVELOPMENT: A SYSTEMS-BASED UNDERSTANDING OF LOCAL IMPACT FACTORS

Keywords: *sustainability; rural water development; Nicaragua; graphical modeling; networks*

ABSTRACT

The success or failure of rural water systems is a result of numerous factors that interact in a complex set of connections that are difficult to separate and identify. This research effort presented a means to empirically reveal the interactions of factors that influence rural water project success or failure in Darío and Terrabona, Nicaragua. To accomplish this, the study employed graphical modeling to build and analyze factor networks. Influential factors were first identified by qualitatively and quantitatively analyzing transcribed interviews from community water committee members. Factor influences were then inferred by graphical modeling to create factor network diagrams that reveal the direct and indirect interaction of factors. Finally, network analysis measures were used to identify "impact factors" based on their influence within each factor network. Findings from this study showed the systematic nature of such factor interactions in both Darío and Terrabona, and highlighted key areas for programmatic impact on project success for both municipalities. Specifically, in Darío, the impact areas related to the importance of community water committees, while in Terrabona, the impact areas related to the importance of appropriate project implementation and capacity building by external organizations. Overall, this study presents a rigorous and useful means to identify impact factors as a way to facilitate the thoughtful planning and evaluation of rural water services in developing countries.

INTRODUCTION

The challenges of providing sustainable access to rural water services in developing countries often go far beyond that of the technology itself (Chatterley 2012; Kaminsky 2014). Indeed, many water projects tend to fail or operate suboptimally due to a myriad of social, environmental and political factors that confound long-term system functionality (RWSN 2010; Lockwood et al. 2003; Wateraid 2011; Davis 2014). In most cases these factors are interconnected. As a result, they interact as a system, producing outcomes that are often difficult to plan for or adapt to (WaterAid 2003; Sara and Katz 1997; Wateraid 2011; Ramalingham et al. 2008; Ramalingham 2014). While water sector literature has identified a number of important factors that affect the sustainability of rural water infrastructure, there is limited research that specifically addresses the systemic nature of factor interactions. Improving understanding on how factors interact as a system would aid in more thoughtful rural water project design by allowing practitioners to plan initiatives that target specific *programmatic areas* that yield the greatest overall impact, which this study calls *impact factors*. Thus, the aim of this study was to investigate how factors that influence rural water project sustainability actually interact as a system.

To accomplish this aim, the study used qualitative and quantitative data analysis methods that culminate with *graphical modeling* to display this systemic interaction of factors that in the form of *factor networks*. The techniques presented in this paper are demonstrated using a case study of rural water system functionality in Darío and Terrabona, Nicaragua. Specifically, this study aimed to answer the following research questions:

- RQ1: What are the factors that influence functionality of rural water services in Terrabona and Darío Nicaragua?
- RQ2: How do these factors form interconnected networks?
- RQ3: Based on an understanding of factor interaction as a network, what are the most important factors for long-term functionality of rural water services in Darío and Terrabona?
- RQ4: How do systemic factor interactions differ between Darío and Terrabona?

To answer these questions, data was obtained using semi-structured interviews with community water committee members in charge of water system maintenance in Darío and Terrabona Nicaragua. Interviews were then analyzed to identify recurring factors that appeared influential to water project sustainability. Once these factors were identified, graphical models were used to map conditionally-dependent connections that existed between these factors as a way to build factor networks. Factor networks were then structurally analyzed using *point* and *graph betweenness centrality* measures to identify impact factors. The findings from this research are presented as programmatic recommendations for Darío and Terrabona based on the identified impact factors

BACKGROUND

The identification of influential factors for project sustainability – along with development of assessment and evaluation methods to analyze the impact of these factors on rural water system sustainability – has been the focus of many research efforts within the water sector over the past two decades. As a testament to this level of sector attention on the subject of sustainability, a recent study of water sector literature by Walters and Javernick-Will (2015) identified 93 articles that focused specifically on rural water project sustainability. They identified 157 unique factors that influence long-term water system functionality, which they aggregate down to 25 sub-factors and 8 “sustainability factors” (Table 4-1).

Table 4-1: Sustainability factors found in water sector literature (Walters and Javernick-Will 2015)

Sustainability Factor	Sub- Factors	Definition
Government	Laws & Policy Management Governance	The ability and willingness of local government to provide the necessary expertise and resources to help operate, maintain, monitor, and eventually replace the rural water system.
Community	Participation Demand Satisfaction	The necessary demand present in a community to properly use, operate, monitor, maintain, and eventually replace the rural water system.
External Support	Type of Support Cooperation Post Const. Supp.	An external organization or agency to provide the necessary expertise and resources to help operate, maintain, monitor, and eventually replace the rural water system.
Management	Maintenance Skilled Operator Women Involvement	A water services management scheme to support the permanent and continually high functioning operation of a rural water system through proper operation, maintenance, and monitoring.
Financial	Cost Recovery Financial Management Cost of system or part	A water system management entity (community, external organization/ agency, and/or governing body) to financially support the costs associated with the operation, maintenance and eventual replacement of the rural water system.
Technology Construction & Materials	Spare Part Availability Tech. Appropriateness Construction Quality	Appropriate technology, skilled labor, and spare parts to satisfactorily construct, operate and maintain a rural water system.
Environment & Energy	Resource Management Source Protection Energy Avail/Reliable	The ability of the available water resources to provide a continuously sufficient amount of clean water to meet the long term needs of the community and the ability of the energy infrastructure, typically in the form of electricity, to support the continual water system functionality.
Water System Functionality	Quality	The quality of the water as it compares to the country standards for drinking water quality
	Quantity	The quantity of water provided by the system as it compares to country standards for the requisite amount of water provided per person per day
	Reliability	The duration of continuous operation of the water system without water shortages or system break-downs
	Coverage	The availability of water services to users

Many of these same sustainability factors shown in Table 4-1 have been used as metrics and indicators within quantitative evaluation tools that assess the potential for water project sustainability, both for existing and future projects. In a study by Lockwood et al. (2003), a typology of these evaluation tools was presented as those which either assess sustainability using "tabular analysis" or "regression-based analysis". Both types of tools have advantages and limitations in their application and analytical ability.

Tabular analysis tools evaluate survey data by scoring and aggregating factors to derive a composite score usually presented as frequencies, averages or percentages that relate to some level or threshold of project sustainability (e.g., Hodgkins 1994; WSP 1996; Bhatari 2010; Sugden 2001; WaterAid 2003; Godfrey 2009, 2013; Schweitzer and Mihelcic 2012; USAID 2013). A major benefit of tabular analysis is that the data need not be directly measurable (in the way one measures temperature) to evaluate sustainability, but instead may be interpreted by the researcher using a pre-defined scoring criterion. A substantial limitation of the tabular analysis methods is the inherent subjectivity that may influence the results, potentially making the data biased and inaccurately representing the realities in the field.

Regression analysis techniques measure the significance of the relationship between one or more independent variables (in this case, factors) on one dependent variable (e.g., sustainability, or water system functionality). Statistical techniques used by regression analysis are typically either bivariate or multivariate linear regression (e.g., Narayan 1991; Sara and Katz 1997; MPA 2003; Foster 2013). A major benefit of these techniques is their ability to identify the presence of correlations between factors in a way that limits bias and subjectivity on the part of the researcher. Unlike tabular analysis, however, regression analysis requires that all data be measurable, a point which frequently makes its use considerably more difficult to conduct.

Currently, the most commonly used sustainability assessment tools are based on tabular analysis. In a recent study, Boulenar et al. (2013) evaluated five prominent sustainability assessment tools used by non-governmental organizations (NGO), bilateral and multilateral aid agencies. Their study found that all five assessment tools were based on tabular analysis techniques. This is likely due to the aforementioned difficulties associated with regression analysis techniques, including the fact that in many cases regression analyses are inherently more time-intensive and costly (Lockwood et al. 2003). .

POINT OF DEPARTURE

While both types of sustainability assessment tools presented above have unique strengths and weaknesses, one common weakness is the inability to evaluate or correlate the systemic interaction of factors (Sugden 2003; Jordan et al. 2011). This "systemic interaction" may be thought of as a web of factor influences that are both *direct* (Factor A influences Factor B), as well as *indirect* (Factor A influences Factor C through first influencing factor B). Therefore, an improved evaluation of sustainability would be achieved by considering these direct and indirect interactions (Sugden 2003).

This study departs from previous work and aims to fill this gap in understanding and practice by investigating a means to assess sustainability using a systems-based analysis of factor interaction. The technique exploits strengths of both tabular and regression analysis by first collecting and analyzing case study data to find and score factors, and then using these data to probabilistically identify factor interaction and impact through graphical modeling and betweenness centrality, respectively.

RESEARCH METHODOLOGY

The methods applied in this study focus on empirically identifying and evaluating the systemic interaction of factors that influence rural water project sustainability in Terrabona and Darío, Nicaragua. To this end, the research employed a multi-method approach that culminates with graphical modeling to build factor networks, and network analysis to structurally analyze these networks to find impact factors. The requirements for graphical modeling and network analysis guided the selection of the subsequent research methods. First, interviews and community water system assessments were conducted within community water committees and households in Darío and Terrabona, Nicaragua. Second, these data were qualitatively coded to identify pertinent factors (addressing RQ1) and quantitatively categorized as binary variables to aid in quantitative modeling. Third, data were entered into a graphical modeling software which iteratively built dependence graphs that display the interaction of factors within factor networks (addressing RQ2). Lastly, these factor networks were structurally analyzed to infer factor importance based on betweenness centrality (addressing RQ3), thereby facilitating a thoughtful discussion on water planning strategies for Darío and Terrabona (addressing RQ4).

DATA COLLECTION – CASE STUDY

The municipalities Terrabona, and Ciudad Darío (Darío), Nicaragua were chosen for this study because of their relative differences in population, improved water coverage, stakeholder management schemes (municipal governments; non-governmental organizations; community water committees), and a large difference in overall water system functionality. Moreover, their proximity to each other minimized the potential of confounding issues of spatial disparity, as Terrabona and Darío are 16 kilometers apart and are both within an approximately two hour drive from the capital city, Managua. Additionally, Darío has far greater access to financial and material resources than Terrabona. As a result, Darío has installed water systems in over 90% of the communities within the municipality, compared to 77% coverage in Terrabona. These similarities and differences between Darío and Terrabona provided a compelling contrast for impact factors. A comparison between many of these different municipal attributes as they relate to the percent of improved water infrastructure coverage, along with the percentage of water systems in each community that were functioning properly at the time of sampling, is shown in Table 4-2 (El Porvenir 2013).

Table 4-2: Terrabona-Darío comparison

Municipality	Population	# Communities	% Coverage	% Functioning
Ciudad Darío	38,000	150	90	86
Terrabona	13,000	61	77	54

The case study method using qualitative data collection and analysis was chosen to provide rich, process-based insight into research questions that are exploratory in nature, and was deemed well-suited for the purpose of collecting data that provided insight into factor interaction (Yin 2002; Maxwell 2004). A multiple-site case study was chosen for its ability to obtain data that can be spatially and contextually interesting. Conjointly, this provides a more compelling and robust foundation for the propositions made within the data analysis and interpretation process (Yin 2002; Herriot and Firestone 1983). The cases were *embedded multiple case* designs, where the *embedded unit of analysis* was set at the community level (Yin 2002). In other words, the unit of analysis within Terrabona and Darío was set at the community itself where a particular water system exits. In each of the municipalities, data were collected by semi-structured interviews with community water committee members and through observations taken while in each community. Community water committees are elected members from the community who are in charge of the basic operation and maintenance of the community water system. For this interview process, each community was randomly sampled. Throughout the three-month case study time period, it was possible to visit 32 randomly sampled communities in Darío and 22 in Terrabona.

Interview questions were intentionally kept open-ended and directed towards various aspects that could influence functionality of rural water infrastructure within each community. An influence on water system functionality was considered to exist if said factor were to influence water quality, quantity, or continuity (reliability) of the water provided by the system. For example, questions were asked such as, “How well is your water system functioning”, and, “Have there been situations where the water system is not functioning properly? If so, why?”. These types of questions allowed water committee members to tell meaningful stories about how or why their water system was functioning and later provided the needed data for qualitative analysis used to identify factors.

Observational data focused primarily on factors related to the functionality of the water systems themselves, specifically, water reliability (how often the water system was out of service), and water quality. System reliability was assessed by asking interviewees to indicate how often the water system is out of service. Water quality was evaluated by: (i) water quality tests and (ii) the identification of potential pollution risks (presence of nearby animals, pit latrines, etc.). Water quality at the time of sampling was based on the presence or absence of fecal coliforms using PathoScreen Field Test kits which take 24 to 48 hours to display presence (sample turns black), or absence (no perceivable color change in sample) (Hach 2015).

DATA ANALYSIS – QUANTIFICATION

Interviews were transcribed and then analyzed for emerging themes through the process of *qualitative coding* following the best practices of Miles and Huberman (1994), using QSR NVivo 10 software (QSR International Pty Ltd. 2012). Qualitative codes were used to identify portions of transcribed text that fit within recurring themes and patterns that existed between interviews. Specific attention was paid to factors that appeared to relate to the long-term functionality of infrastructure (e.g., finances, existence of a water committee, etc.). All codes were then aggregated into themes, and then into factor groups to allow conversion of the data into a quantitative format to later be analyzed with graphical modeling. Although the process of minimizing the number of variables in the model through theme and factor aggregation presumably simplified the complexities present in both Darío and Terrabona contexts – the authors felt any gains in providing a richer description in the form of more factors would later present difficulties in interpreting model structure for reasons mentioned later in the methods section regarding model fitting.

The quantitative format for data was kept discrete, either “yes” or “no” for each factor to aid in graphical modeling. This process eliminated subjective scoring and subsequent bias on the part of the researcher. As an example of binary factor quantification, if one particular reason given by an interviewee for why their water system was not functioning properly was the “insufficient maintenance and financial support due to frequent conflicts between community members” – the factor “conflicts” would be marked as “yes” for that particular community sampled. If the same community experienced substantial seasonal fluctuations in groundwater level which often caused water shortages, the factor “water resources” would be marked as “yes” as well for that community. In summary, what resulted from the qualitative analysis was a list of recurring factors that emerged between each community, where the presence or absence was then quantified for each factor as either “yes” or “no” for each community.

DATA ANALYSIS – GRAPHICAL MODELING AND NETWORK ANALYSIS

Graphical modeling is a tool for performing multivariate analysis that uses networks to represent models through the identification and subsequent graphing of conditional dependencies between model variables (Edwards 2000, Højsgaard 2012). In these networks, vertices (nodes) are connected by lines (edges) if a conditional dependency exists. Conversely, the absence of a line indicates a conditional independence between two nodes. For example, in Figure 4-1 it can be seen that one edge between nodes is not drawn, namely $[CD]$. This means C is conditionally independent of D given the configuration with A and B, or $C \perp D \mid A, B$, which means there is no line drawn between C and D. An absence of this connection presumably means that C and D do not influence one another. In this study, graphical modeling provided the ability to build factor networks, where network nodes represented factors, and lines represented influences between these factors.

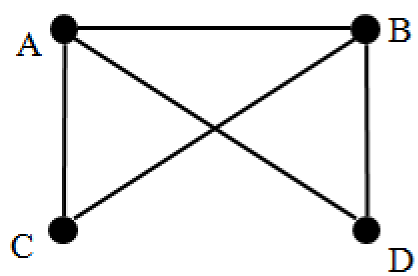

Figure 4-1: An example graphical model

<u>*Graphical Model Fitting*</u>

In graphical modeling, *log-linear models* are typically used to fit discrete data, whereas graphical models using continuous data are typically based on multivariate normal distribution analogous to log-linear models, also known as *Gaussian graphical models* (Edwards 2000). Since the data in this study were discrete (dichotomous) data, a log-linear model was used to fit the data sets. One of the primary difficulties with using graphical modeling to fit a multivariate data set is choosing between a myriad of different well-fitting model structures (Whittaker 1990). This is because in the case of even a 15 node undirected graph (a model where edges are not explicitly directional), the number of possible undirected graphs is 4.05 x 10^{31} (Højsgaard 2012). Thus, the likelihood of having the true optimally best-fit model is small, especially when the number of variables is high. However, in the case of this research, an optimal fit was deemed less important than a "good-fit" model that helps gain insight into the implication of systemic factor interaction (Amadei 2015).

Because this research focuses on the exploratory development of factor structures, this study used a *stepwise method* of model selection (Edwards 2000; Højsgaard 2012). The stepwise model selection method is an iterative process where a graphical model (in this case, a factor network) is chosen that optimally fits a particular statistical criteria for model significance. Højsgaard (2012) suggests a criteria based on maximum likelihood, which considers a set of models Ɛ(j) for $j = 0, 1, \dots, R$, where the best model is selected based on the Ɛ(j) that minimizes -2log$L(j) + kp(j)$, where L is the maximum likelihood under the model and $p(j)$ is the number of free parameters in the model Ɛ(j), and k is a penalty parameter. Two popular values for k are 2 (Akaine Information Criterion (AIC) (Akaine 1974)) and the Bayesian Information Criterion (BIC) (Schwarz 1978) which sets k = log(N), where N is the number of observations.

With the designation of emergent factors into a binary data format (performed in the previous section), it was possible to run a stepwise analysis to iteratively fit probabilistic dependencies between factors. R-Project statistical software was used to perform these analyses using the packages *gRim* to perform the graphical modeling analyses, and *igraph* to plot the graphical model (Højsgaard 2013). Once a graphical model was built for both Terrabona and Darío, these models were structurally analyzed with betweenness centrality. Betweenness centrality was the choice method for structural analysis as it allowed the evaluation for how factors "bridged" to one another as a system, thereby identifying the structural importance of each factor as a function of the other factors (Freeman 1977; Scott 2000; Borgatti 2005). For this study, betweenness centrality was used to see how factors structurally combine together to directly and indirectly influence sustainability of rural water infrastructure in Terrabona and Darío.

Betweenness centrality scores were calculated both for the factors themselves (known as *point centrality*) as well as for the entire graph (known as *graph centrality*). Point centrality (from this point forward referred as *factor centrality*) scores were calculated for each factor to allow for factor comparison to identify impact factors. Calculation of factor centrality scores was accomplished by analyzing the resulting *adjacency matrix* for each graphical model using the R-package *statnet* (Acton and Jasney 2012). The adjacency matrix houses information regarding where edges exist between nodes in a network. The equation used to calculate a betweenness score for an undirected graphical model (a model where edges are not directional) is shown below. Betweenness scores for Terrabona and Darío graphical models were then ranked from high to low to allow a basis for score comparison using the equation below:

$$C'_B(p) = \sum_{o \neq p \neq q} \frac{\sigma_{oq}(p)}{\sigma_{oq}}$$

Where:

$C'_B(p)$ = the betweeness centrality score for a particular factor
p = the factor of interest
σ_{oq} = the total number of shortest paths that pass between factor o and factor q
$\sigma_{oq}(p)$ = the number of those shortest paths that pass through factor p

Graph centrality (from this point forward referred as *network centrality*) allowed for additional structural comparison between the whole factor networks built for Darío and Terrabona by direct comparison between graph structures using the normalized distribution of point centrality scores (Freeman 1979). Calculation of network centrality required the use of factor betweenness centralities $C'_B(p)$, for each graphical model. These factor betweenness centralities were used to find network centralities for Darío and Terrabona using the equation below, which compares the largest factor betweenness score within a factor network with all other scores in the network (Freeman 1979).

$$C_B = \frac{\sum_{i=1}^{n}[C'_B(p^*) - C'_B(p_i)]}{max \sum_{i=1}^{n}[C'_B(p^*) - C'_B(p_i)]}$$

Where:

C_B = the normalized network centrality score
$C'_B(p^*)$ = the most central factor for based on betweenness centrality
$C'_B(p_i)$ = betweenness centrality for each factor in the network
$max \sum_{i=1}^{n}[C'_B(p^*) - C'_B(p_i)]$ = the maximum graph centrality based on betweenness, for a wheel or star = $n^3 - 4n^2 + 5n - 2$, used to normalize the network centrality score
$n =$ the total number of factors in the graph

Factor Network Building:

To build factor networks, the binary factor data were first imported into R-Project. Then, these data were fit with a log-linear model using the *dmod* function of *gRim*, designated as an undirected graph, since the direction of influence was assumed unknown. A best-fit model was then selected using the *stepwise* function of *gRim* considering the statistical criterion as AIC and the type of analysis based on *decomposable graphs* to enable calculation of MLE with the penalty parameter, k, set to 2 for a true AIC model fit, per best modeling practices (Højsgaard 2012). The *stepwise* function performs a stepwise analysis of either *backward selection* (removing lines from an initial graphical model, where lines initially exist between all factors at the first iteration) or *forward selection* (adding lines between factors, where no lines initially exist at the first iteration). However, for the model fitting in this study, backward selection was chosen per best practices indicated by Højsgaard (2012). Then, *igraph* was used to plot the emerging factor dependency graph (factor network), and each factor network was analyzed as an adjacency matrix using the *betweenness* function of *statnet* with the analysis mode set for an undirected graph to calculate factor centrality. These factor centrality scores were then ranked for later comparison. Lastly, network centrality was calculated for both Terrabona and Darío graphs using the factor centrality scores from the previous step. The overall process for building graphical models used to create factor networks and perform structural analyses, is shown in Figure 4-2.

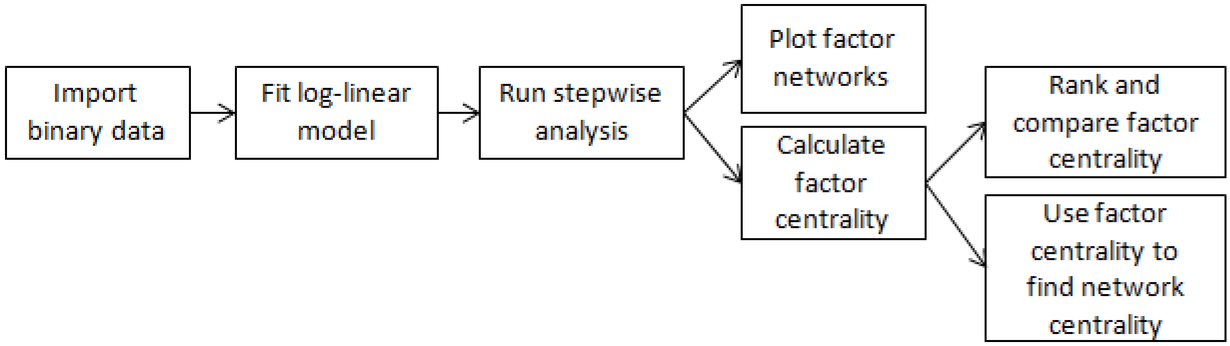

Figure 4-2: The factor network building and analysis process

RESULTS & DISCUSSION

This section presents the results of the analyses from the data collected in Darío and Terrabona. First, it presents and describes the factors that emerged through qualitative analysis of the interview and survey data, and then describes the method and rationale for factor quantification. Second, it displays the results from the graphical modeling and discusses similarities and differences between factor interaction in the context of Terrabona and Darío using betweenness centrality measures. It then proceeds with a discussion of the findings from these analyses.

FACTOR IDENTIFICATION AND QUANTIFICATION

The transcribed interviews coupled with field observation allowed for the coding of recurrent themes between the communities in Darío and Terrabona. Recurrent themes were coded for two reasons: (i)because they signified factors that were consistently important for long-term water system functionality; and (ii) because graphical model building required the use of consistent factor comparisons for each sampled community to evaluate conditional independence between factors. Themes of interest related specifically to aspects that appeared to enable or hinder the long-term functionality of the water system. For example, one important recurring theme – community "organization" – appeared to influence the community's ability to make timely water system repairs, as mentioned by one water committee member:

> *"If there is a problem with the water system it always gets resolved quickly because of the level of organization we have in the community. When we say we need to organize, we always do it, including when we need to clean up garbage in our community"*.

Below is a similar example for the recurring theme of water user fees (tariffs):

> *"Members of this community need to pay 20 pesos per month for their water services. If they don't pay we cut their water services."*

In this same way, each recurring theme that related to an effect on long-term functionality was noted and classified (Table 4-3). Each of these themes was then aggregated into factors to create a model that was easier to interpret, while preserving contextual richness (Højsgaard 2012).

Table 4-3: Coded themes

Themes	Definition
Organization	Organization of the community: regularly holding and attending meetings to discuss aspects of water system maintenance
Conflicts	People refusing to pay their user fees causing problems with tariff collection and saving
Source Protection: Clean	Cleanliness around the source: free from garbage that could seep into the water table
Source Protection: Fenced	Area around the source is fenced off from animals to avoid fecal contamination
Source Protection: Forested	Area around the source is forested to ensure an accessible water table
Government Support	Consistent support offered by the government: technical, material, and soft resources (training and education)
Water Committees	The existence of a water committee to manage the water system
Road Conditions	Viable transportation into and out of community all year to acquire necessary materials for water system maintenance and repair
Material Availability	Having ready access to quality materials
Appropriate Tech.	Technology is affordable for the community
External Support	Consistent support from an outside organization, both technical and training
Tariff Payment	Monthly collection of user fees to maintain sufficient savings
Sufficient Savings	A savings account to pay for system maintenance and repairs
Water Shortages	Reliability of the service in providing water all year round
Water Quality	Water quality based on the presence of fecal coliforms
Water Quantity	Sufficient water (over 20 liters per person, per day (Howard and Bartram 2003) is provided to users

Table 4-4 shows how the themes above were aggregated within the factor groups: *Water System Functionality, Community, Government, External Support, Finances, Water Resources, Technology, Infrastructure,* and *Management*. For example, as the predominant water system management scheme that exists in both Darío and Terrabona is "Community-based Management" (a management scheme where the community is solely responsible for the operations and maintenance of the water system) the theme *Water Committee* was changed to the factor *Management*. Similarly, because all three aspects of source protection are important for water quality (fencing to keep out animals and overall cleanliness around the source) and quantity (forestation), these three themes were combined into the factor *Water Resources*. In this way, each theme was placed within a factor group, where in many cases the factor group housed only one theme.

Once factors were created, data quantification entailed reviewing each interview and designating either "yes" or "no" for the presence or absence of each factor for each community. For example, in the case of *Water System Functionality*, if water quality tests in a community revealed the source was clean (no presence of fecal coliforms) AND if members of the households both indicated enough water was available in ample amounts all year round –"yes" would be designated in the place of *Water System Functionality*. Thus, quantification of each factor followed a similar rationale, as displayed in Table 4-4. While this form of factor quantification introduces potential subjectivity, strict attention to consistency was maintained, and the process was undertaken in order to facilitate the next step of graphical modeling using binary factor values.

Table 4-4: Factors

		Criteria	
Factor	**Associated Theme**	**yes**	**no**
Water System Functionality	Water quality, quantity, and shortages	all 3	<all 3
Community	Organization of the community: regularly holding and attending meetings	yes	no
Government	Community frequently receiving help from government	yes	no
External Support	Community frequently receiving help from organizations	yes	no
Finances	Regular collection of monthly user fees, and sufficient savings	both	<both
Water Resources	Protection of the source: clean surrounding, fenced and well-forested	all 3	<all 3
Technology	Appropriate technology: viable supply chain and cheap materials	both	<both
Infrastructure	Viable transportation into and out of community all year	yes	no
Management	Existence of a well-organized community water committee	yes	no

STRUCTURAL ANALYSIS OF FACTOR NETWORKS

By identifying and quantifying factors in binary terms (yes or no), it was possible to build graphical models to represent factor interaction for Darío and Terrabona. The factor networks that emerged from these analyses for Terrabona and Darío are shown below in Figure 4-3. In these networks, the circles represent factors and the lines represent a conditional dependence between two factors.

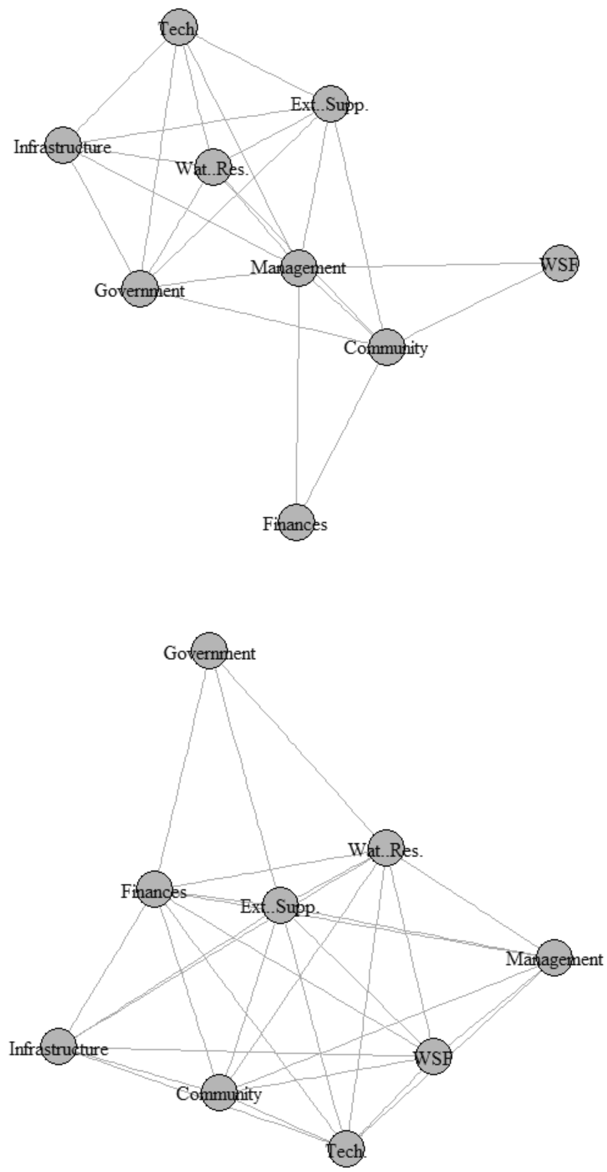

Figure 4-3: The graphical models for factors in Darío (top) and Terrabona (bottom), WSF = Water System Functionality.

GRAPHICAL MODEL INTERPRETATION

The completion of the factor and theme identification in addition to the network graph construction provided the starting point for graphical model interpretation. This step in the process would effectively allow the researcher as well as policy maker to identify the connections – as well as absence of connection – between the factors that influence sustainable rural water systems. Specifically the graphs allow analysis of direct and indirect influences between the factors and the final water system performance.

By direct observation of the graphical models presented above (Figure 4-3), it can be inferred how each of the factors are directly *and* indirectly connected with the factor *Water System Functionality* (WSF in Figure 4-3). In the case of Darío, the factor *Water System Functionality* is directly connected only to *Management* and *Community*, meaning there are more *indirect* influences on water system functionality that direct. For Terrabona, *Water System Functionality* is connected to *all* factors other than *Government,* meaning there are more *direct* influences on water system functionality than indirect. It may also be seen that this lack of connection between government and water system functionality is one main similarity which exists for both Darío and Terrabona factor networks. On the whole, *Water System Functionality* in Terrabona appeared to be influenced by more factors than it is in Darío. These graphical images give a concrete tool to assist in approaching projects in these two locations in a very different manner.

A second level of graphical analysis may now be performed using the centrality measures introduced in Table 4-5 below. Table 4-5 demonstrates that structural differences exist between the factors for the two municipalities. High factor centrality scores imply importance or impact for these factors, due to their ability to bridge between other factors that potentially influence *Water System Functionality*. In the case of Darío, the ranked betweenness scores indicate the most impactful factors are water system *Management* (ranked 1) and *Community* (ranked 2). In the case of Terrabona, *Water*

Resources, External Support and *Finances* were found to be most important (ranked 1), whereas compared to Darío, *Community* was found to be less impactful (a lower factor centrality). These implications in betweenness scores are reinforced with an overall graph centrality sore of 0.1317 for Darío and 0.0234 for Terrabona, meaning factor centrality scores are greater in Darío (indicating higher potential impact) than in Terrabona. Therefore, because Darío has higher factor centrality scores overall, it is easier to identify areas where strategic programmatic changes may have the greatest impact, since *Management* and *Community* are clearly the top-ranked factors. It is more difficult, however, to locate impact areas for Terrabona, which has three factors that are in the top rank, and lower scores than Darío's for these top ranked factors.

Table 4-5: Ranked factor betweenness centrality scores for Darío and Terrabona based on the graphical models (normalized network centrality scores on bottom row)

Rank	**Darío**[1]		**Rank**	**Terrabona**[2]	
1	Management	4.000	1	Finances	1.833
2	Community	2.750		Water Resources	1.833
3	Water Resources	1.417		External Support	1.833
	Government	1.417	2	Community	0.166
	External Supp.	1.417		Wat. Sys. Funct	0.166
4	Wat. Sys. Funct.	0		Technology	0.166
	Finances	0	3	Infrastructure	0
	Infrastructure	0		Government	0
	Technology	0		Management	0
Normalized network centrality score: [1]0.1317; [2]0.0234					

SYSTEMS-BASED INSIGHT

Factor networks provided a structure that can be used to compare field observations with the findings from the structural analysis of factors. Using the factor networks (Figure 4-2) and betweenness score table (Table 4-5), certain correlations were found to exist between observations in the field and the findings inferred by the graphical models. For example, Darío has considerably greater economic prosperity, and in essence, is in a different stage of development than Terrabona. As a result, Darío has previously had more financial capital invested to implement water projects and hold trainings to build the capacity of communities to manage their water system. At this phase of development, the crucial elements for project success would logically hinge on effective *management* of the water services, thereby requiring an organized water committee and community. The importance of management and community is supported by a quote from a water committee and community member in Darío where a water system had been functioning for over 10 years (and was functioning at the time of sampling):

> *"Why is the project functioning so well? In my opinion, and I'll tell you why, is because of good maintenance. If a water system is not maintained, it certainly will stop working. But even to this point, and certainly we're not perfect because this is impossible, but we are organized and we have been organized to achieve a water system that has functioned so well these past years."*

In contrast, Terrabona, as a far poorer municipality, has substantially less access to resources and has not installed as many water systems. This fact places them in a different phase of development than Darío, one in which the impact factors are logically focused on the need for reliable and clean water, finances, and external support. This implies that while management and community involvement are certainly important in Terrabona, perhaps more important are the more rudimentary aspects of water system functionality (available money, a clean water source) enabled through external support from the local government or an organization. In fact, while many water projects in Terrabona were seen to have issues with overall functionality, those that were most successful had high levels of external support to provide money and resources for new and existing water systems. As one water committee member in Terrabona remarked:

> *"Last year our water system had issues with broken pipes and sand clogging the system. But, thanks to* [an NGO] – *who provided help with money and new tubes to fix the problem – the water system is working again. They also continue to provide workshops to help us learn more about maintaining the system to avoid this happening again."*

Based on these findings, it is possible to offer recommendations for organizations working in Darío and Terrabona. For example in Darío, it would appear best to invest resources in building "soft abilities"; investing resources in the form of trainings to build water committee capacity to manage their water system. For Terrabona, due to the area's issues of access to materials as well as issues with money, further external support would be needed to elevate the level of water service access. Conjointly, it would be important to build up appropriate community management infrastructure, empowering community members to finance the operation and maintenance of their water system.

Having a systemic understanding of factor interaction therefore offered key insights into programmatic changes that would target potential impact factors through policy or direct implementation of water service management strategies in Darío and Terrabona. Overall, the findings from the graphical models match well with the present realities in Darío and Terrabona observed by the authors, and successfully answer the research questions.

CONCLUSIONS & STUDY IMPLICATIONS

This study presents a means to empirically identify the structural interaction of factors that influence rural water system functionality. This methodology was demonstrated through a case study conducted in Darío and Terrabona Nicaragua.   Specifically this research aimed to gain understanding of factor interaction and importance as a means gain insight into impact areas for strategic planning.

Findings from this study showed marked structural differences between factors networks for Terrabona and Darío. For Darío, the two highest scoring (and therefore highest impact) factors were Management (1) and Community (2). This means the presence of a well-organized water committee and highly involved and trained community would be most impactful for the success of the water system. For Terrabona, however, three factors held the top rank: Finances, Water Resources, External Support. Based on the factors characterized in this study, this suggests that the factors crucial for water system sustainability in Terrabona are (i) sound tariff schemes to ensure sufficient funds for operation and maintenance of the water system, (ii) the aid of external support to help with the initial stages of project implementation and management and (iii) the importance of a viable water source that provides sufficient clean water throughout the year.

The implications of these results indicate a substantial difference for where practitioner should focus their resources in each of these municipalities. For example, these results suggest that practitioners working in Darío should focus their efforts in ensuring community water committees are well organized. However, this does not imply that the rest of the factors are less *influential*, since without clean and plentiful water resources, or a well functioning water system or technology, the system would certainly not be sustainable. What this does mean is that, given the present phase of development in Darío, a well organized community or water committee is more impactful on project success than other factors. In terms of the factor network for Darío, the direct influence of *Management* and *Community* were found to have the greatest impact on *Water System Functionality*, where the strength in *Management* and *Community* factors hinges on the indirect influences of the other factors.

Practitioners working in Terrabona would need a different strategy, as the results in this study indicated the most impactful factors are the existence of reliable and clean water, viable finance schemes, and external support by the government and organizations. This implies that even though management and community involvement are highly important, possibly the most important are more rudimentary aspects of water system functionality (i.e., money, water itself) given the help of external support. Thus, in a community such as Terrabona, which is at a lower stage of development than Darío, the type of programs and policy interventions that will be successful will be quite different than those that will be successful in a community like Darío.

Overall this study presents a novel and useful way to infer the systemic interaction of factors that influence rural water system sustainability in developing countries through the creations of factor networks. These factor networks were shown to enable the emergence of impact factors that informed recommendations for strategic planning and resource allocation for rural water systems in Terrabona and Darío. Additionally this research provides an interesting theoretical contribution by providing evidence of the interconnectedness of factors, and the importance of context on factor interaction. This connectedness and interaction would not be possible to identify in traditional quantitative and qualitative methods. It is only through the intersection of these methods in the graphical form – using methods such as graphical modeling – that the highly interrelated nature of a complex issue such as rural water supply management become apparent and allow policy makers to focus on the areas with the greatest opportunity for impact.

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CHAPTER 5 – SUMMARY OF MAJOR FINDINGS AND CONCLUSIONS

"Being less surprised by complex systems is mainly a matter of learning to expect, appreciate, and use the world's complexity."

- Meadows 2008

"Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful".

- Box and Draper 1987

"A reinforcing feedback loop [was] *drawn by three first-grade boys that helped them take an endogenous view and see their own roles in their repeated playground arguments and they owned it. Realizing that mean words hurt feelings and set up the likelihood of more mean words enabled the boys to think about ways they could break the spiral. The boys have internalized at least some of the lessons here. At one point two of them got into an argument cleaning up the classroom, tussling over putting away the same chair. The third interrupted them: 'Guys! Remember the loop!' And the two fighting over the chair backed off, each offering it to the other to take care of: 'You take it.' 'No, you….' They* [were] *beginning to see themselves in the dynamics they experience."*

- Richardson 2011

INTRODUCTION

The body of this dissertation (Chapters 2 through 4), presented three unique studies that share the unified objective of gaining insight into rural water service sustainability in developing countries by mapping and analyzing the interaction of influential factors. The purpose of this final chapter is to summarize the combined findings of these three studies, and to discuss their theoretical and practical implications as a whole. Additionally, this chapter aims to highlight potential limitations that exist as a result of the research methods employed, and proposes future research that might address these limitations while fortifying and expanding upon the exciting prospects of system-based analysis techniques for sustainable development.

MAJOR FINDINGS – CONTRIBUTION TO WATER SECTOR THEORY

This research provides two overarching theoretical findings that contribute to the water sector body of knowledge regarding the complex aspects of rural water service provision in developing countries, and the merit for systems approaches that consider the complexities inherent in rural water service development. First, it showed that although many of the same factors were found across the studies to influence long-term rural water functionality based on literature, expert and stakeholder opinion, and field data; the way in which factors *interact* is largely dependent on context. Second, it presented clear evidence that the factors that influence long-term functionality are interconnected as a complex system and change over time. These major findings are presented in more detail below.

THE INFLUENCE OF CONTEXT ON FACTOR INTERACTION

Factor interaction (or "structure") was found to be largely controlled by the region of study (i.e., Terrabona and Darío, Chapters 3 and 4), and the opinions of the experts and stakeholders (Chapters 2 and 3). Interesting similarities and differences between factor structures emerged as a result of these two contexts, and provided compelling evidence for the need of sustainability assessment and planning tools that can adapt to unearth, analyze, and consider these complexities for a wide array of contexts.

It makes logical sense that the geographical region of study affects the level of influence from factors on water system functionality, such as the type of technologies and construction materials that are available, the type of management schemes that are used, or the environmental constraints that affect water resources. In the same way, one might expect marked structural differences between factors based on the opinions of water experts and project stakeholders within a particular region. However, while the influence of these contexts is indeed obvious, the research presented here demonstrates a novel means to *visually* and *quantitatively* assess these seemingly *invisible* differences. A useful example of the power of the systems-based methods employed in this research can be made through comparison of factor diagrams and networks that emerged in Chapters 2 through 4, again using normalized betweenness centrality scoring. Table 5-1 summarizes this comparison using the normalized factor betweenness scores (factor impact based on point centrality – described in Chapter3 p. 55 and Chapter 4 p. 85), and overall normalized graph centrality scores (entire network – described in Chapter 4, pp. 85), for both opinion and field-based factor networks, respectively. As was done in Chapters 3 and 4 these betweenness scores are normalized from high to low for the purpose of cross-comparison.

Table 5-1: Normalized betweenness score comparison summary from all three studies, where G&P = Government & Politics, Man = Management, T&E = Training & Education, Com1 = Communication, WSF = Water System Functionality, WR = Water Resources, Fin = Finances, Ext = External Support, Tech = Technology, Infra = Infrastructure, Com2 = Community, ND = No Data, Exp = Experts, Dar = Darío, Terra = Terrabona

WC[1]		**Org**[2]		**Gov**[3]		**Aca**[4]		**Exp**[5]		**Dar**[6]		**Terra**[7]	
T&E	0.317	Fin	0.337	WSF	0.400	G&P	0.293	Fin	0.311	Man	0.285	Fin	0.065
Fin	0.291	Com2	0.210	Fin	0.400	Fin	0.125	Man	0.127	Com2	0.125	WR	0.065
WSF	0.227	Tech	0.142	G&P	0.366	WR	0.119	WSF	0.100	WR	0.017	Ext	0.065
Tech	0.071	G&P	0.142	Man	0	WSF	0.072	Com2	0.061	G&P	0.017	Com2	0.006
Man	0.010	Man	0.103	WR	0	Tech	0.042	WR	0	Ext	0.017	WSF	0.006
G&P	0.010	Infra	0.067	Com1	0	Com2	0.042	Tech	0	WSF	0	Tech	0.006
WR	0	WSF	0.019	T&E	0	Ext	0.010	G&P	0	Fin	0	Infra	0
Com1	0	WR	0.000	Tech	ND	Infra	0.007	Ext	ND	Infra	0	G&P	0
Ext	0	Com1	ND	Com2	ND	Man	ND	Infra	ND	Tech	0	Man	0
Infra	ND	T&E	ND	Infra	ND	Com1	ND	Com1	ND	Com1	ND	Com1	ND
Com2	ND	Ext	ND	Ext.	ND	T&E	ND	T&E	ND	T&E	ND	T&E	ND
Normalized network centrality scores: [1]0.241; [2]0.239; [3]0.272; [4]0.263; [5]0.234; [6]0.1317; [7]0.0234													

Base on these cross-comparisons between factor betweenness scoring for both opinion and field-based data one may deduce that regardless of the differences in context, "Finances" is the most impactful factor for the sustainability of long-term water system functionality; namely that sufficient funds are available to operate and maintain the water system. In contrast, the least impactful factor based on opinion and field-based data appears to be "Technology"; namely, the selection of an appropriate technology based on cost, and available materials. These results present additional insight into rural water service sustainability theory by aligning with the shifting focus of the water sector away from technological approaches towards market-based approaches that foster viable income streams for sustaining rural water infrastructure.

In contrast, as a testament of the influence of context on factor interaction, Table 5-1 shows marked structural differences exist between factor networks based on both factor (point) and network (graph) betweenness centrality scores for the opinion and field-based data sources. Differences in these factor structures imply a potential disconnect between what practitioners and stakeholders viewed as impactful on sustainable rural water services versus what field-based evidence shows is impactful. The first representation of this difference is the relative impact of the factor "Water Resources". For water resources, stakeholders and experts indicated a very low impact (other than the Academics stakeholder group), when it fact it was found to be significantly impactful in Darío, and especially in Terrabona based on field data. A second difference exists between the normalized graph centrality for opinion and field data. For opinion-based data, the range in graph betweenness centrality is relatively high (0.234 to 0.272), whereas for field-based data, the range is relatively low (0.023 to 0.132). A lower graph centrality score (such as for the field-based factor graphs) means each factor has relatively the same impact, or in other words, they are all equally influential or "connected". In contrast, a higher graph centrality scores (such as for the opinion-based factor graphs) means one particular factor is comparatively more important than the other factors. This means the factor structures formed by experts and stakeholder opinion revealed factors that were comparatively more important or impactful than what was found in the field, implying that while these practitioners may indicate certain factors are more important than others, it is possible that, in reality, a multitude of factors are equally important and interconnected. These findings place further precedence on fully considering the unique interaction of factors based on the study context, and the importance of considering factor interaction as a system.

THE SYSTEMIC INTERACTION OF FACTORS

This research showed the factors that influence rural water system functionality in developing countries interact as a complex system. While this finding is relatively intuitive (i.e., most would agree that in reality factors are interconnected in a complex way), it nonetheless emphasizes the need for systems methods that can aptly consider these complexities in order to plan and maintain water services that are sustainable. In light of historical research and practices in water service sustainability, this finding implores a paradigm shift in methods that lie outside the traditional forms of assessment and planning (i.e., tabular analysis and regression-based methods), and which instead exploit the advantages of methods specifically created to deal with complex systems.

Thus, this research presents a case for methods that enable systems-based understanding on problems rooted within complex social structures; methods that evolve from a reductionist-based understanding (closed-form, static and linear systems) to a systems-based understanding of a problem (open, dynamic and non-linear systems). In fact, this research provides clear evidence of the systemic and dynamic factor interaction (see Chapters 2 and 4), which, in turn, implies linear thinking will improperly address the core issues that inhibit rural water service sustainability. In the same way, this research successfully demonstrated the use of qualitative and quantitative methods to interpret the complex social aspects of stakeholder alignment (see Chapter 3). As such, this research makes a compelling case for the use of systems methods to understand the complex factor influence on rural water service sustainability in developing countries by effectively demonstrating a compelling use of systems-based tools.

MAJOR FINDINGS – CONTRIBUTION TO WATER SECTOR PRACTICE

Many of the previously mentioned theoretical contributions from this research directly correlate to practical ways to improve rural water service sustainability. Specifically, the resounding importance for sound finances, found to be the most impactful factor, provides impetus for the allocation of resources for existing and future rural water projects. As a practical matter, this requires that viable financial management plans be thoughtfully investigated by researchers and skillfully implemented by practitioners to operate and maintain infrastructure appropriately in different contexts. Also, there is clear disparity in expert and stakeholder opinion (Chapters 2 and 3) regarding how post-construction support should be executed by local government and external organizations, and this creates an additional incentive for investigating effective collaborative water system management plans. The way in which stakeholder alignment facilitates effective infrastructure design and management provides additional incentive for practitioner collaboration that is aligned with the constraints in the field, constraints that this dissertation has shown significantly affect sustainability based on the systemic interaction of factors.

In the process of investigating systemic factor interaction, this research employed a suite of methods which practitioners could conceivably use to improve understanding on rural water service sustainability. In a pilot attempt to demonstrate a potential framework, this dissertation integrates many of the methods employed herein within a framework the author is calling the "Systems-based Sustainability Assessment (SSA) Framework." The proposed SSA framework follows either a 5-step or 10-step model building process that ends with a decision made by the practitioner for strategic action (i.e., implementation, management, and policy) based on the insight gained through system-based factor analysis. The beginning (and requisite) 5-step process is called Structured Group Model Building and Analysis (SGMB), a participatory method which takes place in model building workshops where participants build informative models during multiple workshop sessions. If workshop participants require further information to make their decision, the second 5-step process called Empirical Model Building and Analysis (EMB), offers additional insight into complexity based on the realities in the field through computational modeling using field data in combination with insight from the previous SGMB sessions. An overview of the entire modeling framework is shown in Figure 5-1. A complete overview of the model-building processes may be found in Appendix F.

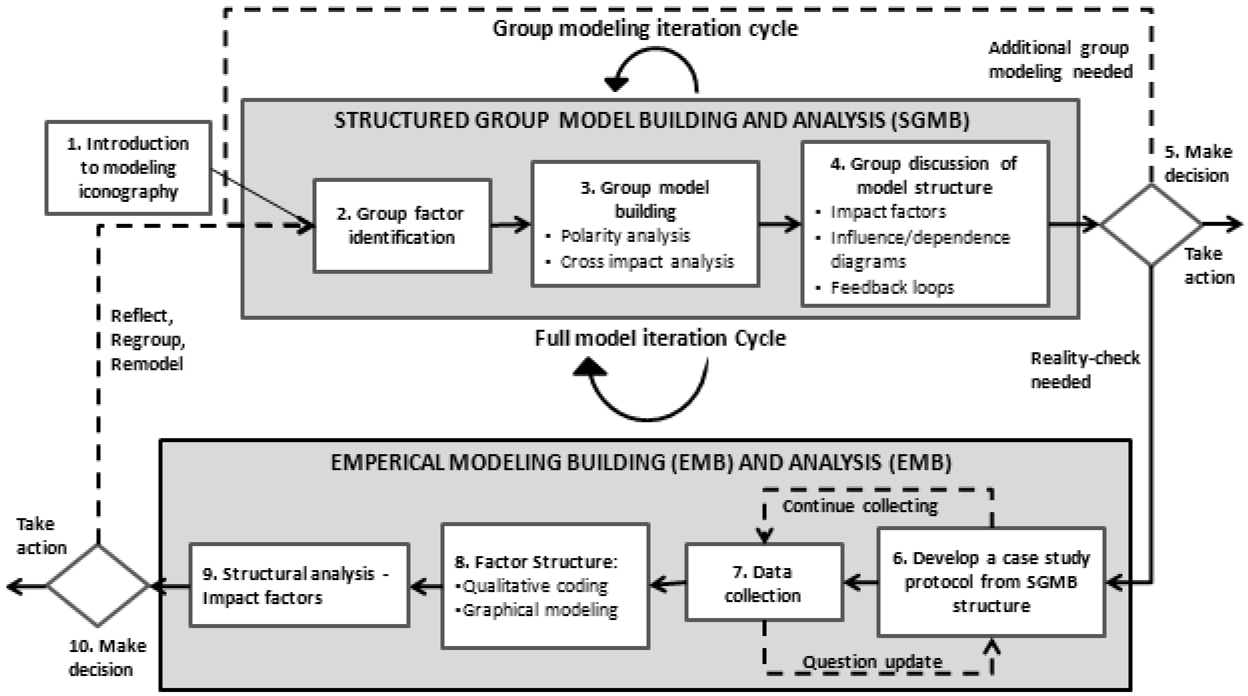

Figure 5-1: The Systems-Based Sustainability Analysis Framework

STUDY LIMITATIONS AND PROPOSED FUTURE RESEARCH

The research presented in this dissertation took one humble step towards improving understanding on the complexity of rural water infrastructure sustainability through systems-based analyses of factor interaction. However, many important limitations exist in this research that must be mentioned in order for future research of this type to be improved upon and profitable.

As a whole, the underlying premises behind the methods of this research were founded on the notion that analyzing the structural interaction between factors offers key insight into the systemic causes of a particular outcome. An unfortunate reality, however, is that structural modeling techniques (i.e., system dynamics, network analysis, and graphical modeling) have an inherent issue with validity; that is, the extent to which the research findings accurately represent the real world (Mohapatra et al.

1994; Sterman 2000; Bossel 2007; Vennix 1996; Mirchi 2012). Specifically, there are two validity concerns associated with structural modeling: *construct validity* (a gap between the problem that is modeled and the model itself), and *internal validity* (the influence between these variables is not true-to-life) (Olivia 1996, Barlas 1996). These inherent validity issues were potentially exacerbated by attempting to model the influence of *soft variables*, such as "Management," "Community," and "External Support," on long-term rural water system functionality. Specifically, the use of soft model variables in this research potentially caused issues with both construct validity (i.e., the model's ability to truly measure sustainability), as well as internal validity (i.e., the factors chosen for the model truly interact as they do to influence sustainability) (Reyes 2003), because modeling soft variables necessitated the use of expert and stakeholder opinion, and required the author to make broad generalizations and simplifications throughout the modeling process. Consequently, the major cause for aforementioned validity concerns is likely *subjectivity* and *bias* on the part of the author and the human subjects used to gather and analyze these data used to build factor diagrams and networks.

For the author, many forms of subjectivity and bias invariably entered the research design and execution. The author's previous experience with rural water service sustainability could have conceivably influenced the research methods for both data collection and analysis. For example, in Chapter 2, the author took the opinions from experts within water literature to create a list of "sustainability factors" based on recurrent themes. It is possible that the selection of these recurrent themes was influenced by the author's own perceptions regarding the important factors for rural water sustainability, perceptions developed from years of taking classes and reading journal articles on the subject of sustainable community development. In this same way, in Chapter 3, biases likely entered into the way the author engaged with the stakeholder focus groups in the subconscious guiding of participants towards important factors and factor influences. Issues with author subjectivity may also be present in Chapter 4 with the coding of important recurrent factors based on the transcribed interviews with water committee members. Examples of author bias and subjectivity such as these give substantial evidence for possible validity issues within the emerging factor structures found in this research.

Similar issues with biases likely entered into the collected data and analyses from the Delphi panelists (Chapter 2) and interview participants (Chapter 4). For example, in Chapter 2, expert panelists had noticeable biases towards a particular type rural water system management scheme (i.e., market based approaches, community based management, post-construction support, etc.), and as a result, had significant variance in their cross impact scoring of factors. Similarly, in the Nicaragua case study (Chapter 4), interview participants had obvious biases towards the interviewers regarding how they perceived the economic status of the interviewer. These biases were often confirmed when an interviewee would ask at the end of the interview: "So, when are you going to bring help?" These examples of participant biases provide substantial evidence for the existent of additional sources for validity issues within the emerging factor structures found in this research.

Lastly, while a powerful attribute of the methods employed in this research was the ability to emerge systemic factor influences, replicating meaningful results within certain regional contexts could potentially be difficult. Indeed, the utility of these methods (as with most research methods) hinges on the type and availability of data sources used. In the case of this research, the data were gathered predominantly from community water committees, which may be considered an organization that has an intimate understanding of their specific water system. In contrast, applying the methods used in this research in other areas where community based management schemes are not used and where water system installation is driven by disparate organizations and corrupt government, could yield results that are both uninformative and inaccurate.

Having highlighted the possible sources of validity issues, the question becomes: How likely is it that the factors found in this research actually describe the real problem of rural water service sustainability in developing countries (e.g., construct validity)? Furthermore, how likely is it that the factor interactions found in this research truly represent how these factors interact (e.g., internal validity)? A reasonable answer to these questions is: there is no real way to tell. Indeed, the act of arguing over the validity of a model structure has nearly the same rational basis as trying to assess validity altogether. To attest to this truth, many systems modeling experts indicate that assessing the true validity of model structures is actually impossible (Forrester 1962; Forrester and Senge 1980; Barlas 1996; Sterman 2000), largely a result of not having access to proper data (Mirchi 2012). In spite of these challenges, the prevailing view of systems modeling experts is that model validity should be based on its "usefulness with respect to some purpose" (Barlas 1996, p.186). In other words, the real benefits from systems modeling manifest in the form of useful information that may be gained by engaging in the modeling process overall, where knowledge gained by the modeler(s) for how system structure influences behavior is far more important than obtaining a "correct answer" (Bossel 2007, Vennix 1996, Box and Draper 1987). The difficulty then becomes less a matter for how well the model is built, and rather how well the modeler(s) exercise discernment and critical reflection when interpreting the results.

Despite the previously mentioned limitations, the author recommends conducting future research that continues to look at the complexities inherent in rural water infrastructure using systems-based tools. In particular, the author recommends focusing on future research that supports or denies the claims presented here by i.) testing and rigorously assessing the ability of the tools used in this dissertation to replicate equally informative insight in different regional contexts, as well as assessing the extent to which certain tools should be omitted or employed; ii.) investigating the use of different systems tools (e.g., quantitative system dynamics modeling, operational research, complexity science methods, soft systems methods, Bayesian networks, etc.) that can better evaluate factor interaction and the resultant outcome on water service sustainability; and lastly iii.) continuing to investigate the proper use of systems modeling frameworks (i.e., the SSA framework presented earlier) to obtain useful information on factor interaction while minimizing the influence of modeler biases. A summary of these recommendations in light of the major findings, implications, and limitations of this research, are shown in Table 5-3.

Table 5-2: Summary of major findings, contributions to water sector body of knowledge (BOK), and recommended future research

Major Finding	Contribution to BOK	Limitation	Future Research
Context largely influences factor interaction	Emphasis on the importance of sound project finances regardless of the regional context Evidence that future sustainability assessment and planning tools must have the ability to unearth influences in varying contexts	Ability of the research methods to reliably replicate meaningful and useful results in different contexts	Rigorous testing of the ability for the research methods to replicate useful results within different country and cultural contexts. Continuing to investigate the use of systems modeling frameworks that minimize modeler biases
Factors interact as an interconnected system	Evidence that sustainability assessment and planning tools must have the ability to consider the systemic and dynamic influences between factors in order to plan for and maintain sustainable water services	Possible concerns with the validity of factor structures as a result of modeler and data biases, as well as the inherent validity concerns with systems modeling	Investigating the application of different systems tools to better identify and evaluate systemic and dynamic factor interaction and the resultant impact on water service sustainability

In summary, the more a person looks into the complexities of sustainable development, the more they realize just how far down the proverbial rabbit hole they must go to gain the breadth and depth of knowledge necessary to truly understand it. However, this is a worthy venture if we must indeed fundamentally reorient and improve the way rural water projects and services are planned, implemented, and managed. Therefore, it is the author's sincere hope that future research efforts continue to investigate the use of systems-based approaches to rural water service sustainability in developing countries.

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APPENDIX A: CONTENT ANALYSIS

This Appendix presents the comprehensive findings from the systematic literature review (content analysis), the first step of this research and first part of Chapter 2. These findings are presented as a raw list of the factors considered by literature to influence rural water service sustainability in developing countries (Table A-1); an ordering of these factors into "sustainability factors" and their associated sub-groups presented in part in Chapter 2, Table 2-1 (Table A-2); and a list of the references included in the literature review.

FACTOR SUMMARY FROM LITERATURE REVIEW

The 157 factors identified in the content analysis are presented below. While many of these factors are self-explanatory, those that are more ambiguous have text in parentheses for additional clarification.

Table A-1: Factors from literature

Influential Factor	Sources	References
Community Capacity	87	409
Project Cost	1	1
Participation	44	53
Socio-cultural Aspects	28	34
Demographics (age, gender…etc.)	5	6
Population Dynamics	12	13
Community Demand	30	40
Accounting (transparency)	24	29
Dispute Plan	1	1
Political Chieftaincy	1	1
Community Championism	1	1
Community Ownership of System	11	14
Initiation (community initiates project)	1	1
Education of Community Members	9	10
Cost (technology)	16	19
Self Supply (model)	1	1
Accountability (organizational)	4	4
Accounting	13	18
Local Entrepreneurship	1	1
Community Criticism	1	1
Community Choice of Technology	1	1

Community Behavior Change	1	1
Social Networks	1	1
Cheaper Water sources	1	1
Community Incentives	4	4
Availability of Cash	2	2
Contracts	1	1
Alternative Sources Available	4	5
Voluntarism	1	1
Human Behavior	1	1
Conflicts in Community	6	6
Unmet expectations	1	1
Capacity of Users	1	1
Com. Participation in decision making	2	2
Decision Making	6	7
Household Income	2	2
Capacity Building (training)	4	5
Community Assets	1	1
Ability to Maintain and Expand	1	1
Self Financed (community)	1	1
Community Organization	2	2
Income of community members	3	3
Initial Upfront Costs	14	14
Community Knowledge	2	2
Motivation & Attitudes (Community)	4	4
Satisfaction and Ownership	22	29
Sweat Equity	3	3
Training – Community	19	21
Trust of Committee	3	3
User Error	5	7
User Income	1	1
Vandalism	1	1
Water Demand	2	2
Willingness to pay	19	22
Water Use	1	1
Financial Capacity	55	98
Economies of Scale	1	1
Economics - water sector	1	1
Donors and Funding	8	9
Financial Needs	42	57
Long Term Costs	1	1
Lifecycle Costs	1	1
Cost Recovery	8	9
Cost Sharing	6	6
Operation and Maint. Costs	2	3
Bank’s Cash	1	1
Ephemeral Funding Mindset	1	1
Adaptability for growth	1	1
Replacement Funds	5	7
Government Capacity	36	60
Governance	6	6
Government Management	19	25

Governmental Involvement	1	1
Economics - government	1	1
Laws Rights, water permits, etc.	21	21
Political Cohesion	3	5
Corruption	1	1
Environment & Infrastructure Capacity	40	59
Environmental Resources	37	47
Ecology	1	1
Quality of Water at Source	1	1
Climate Change	2	2
Energy (solar, energy grid)	8	8
External Support Capacity	39	96
Type of support	15	32
Technological Capacity	2	2
Cooperation	14	18
Efficacy	6	9
Number of Visits from Institution	1	1
NGO	1	1
Lack of Follow up support	1	2
Post Construction Support	12	14
Subsidies	3	5
Visits PCS	3	3
Accounting (organization)	7	7
Political Chieftaincy (institution)	2	2
Technology Construction & Materials	65	143
Quality Construction	9	10
Physical Condition of System	2	2
Project Age	4	4
System Type	4	4
System Age	9	9
Technical Planning, Design,	8	9
Technology	29	36
Technology Type	9	9
Engineering	1	1
Distance to municipality	5	6
Materials (Spare Parts)	31	45
Materials Quality	2	2
Materials Transport and Proximity	1	1
Remoteness	3	3
Tools and Equipment Availability	1	1
Topography	1	1
Functionality RWS	45	129
Use	11	12
Reliability	8	9
Quality	19	22
Quantity	14	18
Operation	26	39
Crowding	1	1
Distance to Source	14	15
Impacts	3	10
Water fetching time	2	3

Management Capacity	89	559
Community Management	49	66
Water Committee Management	18	19
Management	9	10
Monitoring	28	35
Marketing	2	3
Monitoring (Water Meters)	7	9
Operation and Maint. Schemes	1	1
Policy	18	22
Private Sector	8	10
Reflection	3	6
Repairs	5	5
Skilled Maintenance and Repair	29	32
Standardization of components	5	5
Standards (technology)	3	3
Tariff Scheme	48	65
Training – General	17	18
Training – Community	20	22
Use of Funds	1	1
Maintenance	38	56
Maintenance Major	2	2
Circuit Rider	6	11
Chlorine	1	1
Collaboration between stakeholders	6	6
Communication between stakeholders	12	13
Equity	18	19
Information	5	6
Regulations	4	4
Water as a business	1	1
Warranties and Insurance	1	1
Gender Aspects	19	24
Gender	10	12
Incentives	4	4
Institutional Management (Mandates)	46	67

SUB-FACTOR BREAKDOWN

The factors presented in Table A-1 were categorized into sub factors to aid in the process of designating "sustainability factors" (Chapter 2). This process is shown below.

Table A-2: Sub-Factors

Sustainability Factor	TOPIC	SOURCE IN LITERATURE
Government	Governance/ Leadership	Adank 2013, Armanios 2012, Katsi 2007, Zoomers 2005, Carter 1999, Choguill 1996, Lockwood 2011,2012, RWSN 2011, Rojas 2012, UNOM 2003, McConville 2006, Schweitzer 2009.
	Communication/ Coordination & management	Vasques 2013, Harvey 2004, Kleemeir 2010, Lockwood 2013, Rojas 2012, UNOM 2003, Lockwood 2011 Carter 1999, Mackintosh 2003, WSA 2013, Carter 2006
	Laws and regulation, enforcement	Lockwood 2011, UNOM 2003, Adank 2013, Carter 2007, Chatterley 2011, Choguill 1996, Mukherjee 2003, Harvey 2004, 2007, Haysom 2006, Jones 2008, Jones 2012, Kaliba 2002, Lockwood 2003, 2012, 2012, 2013, Musonda 2004, Smits Rojas 2012, Thorston 2007, WSA 2013, Harvey 2004, CARE 2000, WEDC 1998, UNOM 2003, Carter 2006, Chatterley 2012, Mukherjee 2003, DWA 2012, Gross 2001, Lockwood 2003, 2011, Bartram 2009, Musonda 2004, Narayan 1995, Katz 1997, Sutton 2004, WaterAid 2003, Zoomers 2005, Srikanth 2009, WSA 2013, Chatterley 2011
Community	Village identification of the problem, developing schedules, planning, implementation, choice of system	Bartram 2009, Choiguil 1999, Carter 2006, DWA 2012, Harvey 2007, Jimenez 2012, kaliba 2002, WSA 2013, Prokopy 2005, Silva 2013, Thorston 2007, Hook 2006, Katz 1997, Lockwood 2003, Taylor 2013, Graciana 2012, Ramirez 2012, Mihelcic 2012, Sugden 2001, Bagheri, Hjorth 2007, Bandari 2007
	Technical administrative and financial reports kept, good accounting, auditing, transparency	Adank 2013, Chatterley 2011, Godfrey 2009, Lockwood 2012 Suyani, Sust Indicators, RWSN 2011,Schweitzer and Mihelcic 2012, Schweitzer 2009, Smits Rojas 2012, Carter 1999,Mukherjee 2003, Harvey 2004, Kleemer 2000, Prokopy 2005, Katz 1997, Whittington 2009, Wateraid 2011, Thorston 2007
	Behavior: Cheap or alternative water sources, communication, conflict resolution	Harvey 2011, Haysom 2006, Katsi 2007, Gross 2001, Harvey 2004, Whittington 2008, Pushpangadan 2008, Sugden 2001, Armanios 2012, Bartram 2009, Carter 1999, 2007, Choguill 1996, Harvey 2007, Kaliba 2002, Katsi 2007, Whittington 2008, Opong 2014
	Income of people	Adank 2013, Choguill 1996, Harvey 2004, 2007, Jones 2008, Thorston 2007, Prokopy 2008, Musonda 2004, Bandari 2007, Silva 2013, Panthi 2006 Harvey 2007,
	Participation	Mukherjee 2003, Kleemeir 2000, Mihelcic 2012, Haysom 2006, Chambers 2005, Alvarado 2009, Bhattari 2010, Carter 1999, 2006, 2007, Chatterley 2012, Cleaver 1999, Davis 2012, Mukherjee 2003, Glietsmann 2007, Graciana 2012, Gross 2001, Harvey 2004, 2007, Jones 2012, Kaliba 2002, Marks, Davis 2011, Masduqui 2010, McConville 2006, Musonda 2004, Narayan 1995, Panthi 2006, Prokopy 2005, 2008, Schweitzer 2009, Silva 2013, Smits Rojas 2012, Thorston 2007, WaterAid 2011, Wilkinson 2007, Zoomers 2005, Gross 2001,

	Demand, desire to have tech, responsiveness, initial financial contribution, willingness to pay, contribute money, continue paying, perceived need	Carter 1999, 2006, 2007, Mukjeree 2003, Vasques 2013, Hopins 2004, Jimenez 2010, Lockwood 2003, Bartram 2009, Musonda 2004, Parry-Jones 1999, Breslin 1999, Manikutty 1998, White 1997), Prokopy 2008, Katz 1997, Mihelcic 2012 Schouten 2005, Sutton 2004, Thorston 2007, Wateraid 2011, Hopkins 2004, Gross 2001, Jimenez 2010, Chatterley 2011, Harvey 2004, Jones 2012, Kleemier 2000, McConville 2006, Narayan 1995, Prokopy 2005, Katz 1997, WaterAid 2011, Abramson 2011, Goss 2001, Harvey 2004, Thorston 2007, Abramson 2011, Bhandari, Chatterley 2012, Graciana 2012, Hopkins 2004, Jones 2008, Kaliba 2002, Lockwood 2003, McConville 2006, Bartram 2009, Chambers 1994, Musonda 2004, Katz 1997, Schweitzer 2009, Sutton 2004, Wande 2010, Whittington 1990, WSA 2013
	Demographics, Population dynamics: age, education level, relationships, gender, creating market, who gets served	CARE 2000,WEDC 1998, Kleemeir 2010, Whittington 2008, Lockwood 2003, 2011 Hopkins 2004, Prokopy 2008, Bhandari, Graciana 2012, Hopkins 2004, Jones 2008, 2012, Prokopy 2008, Schweitzer 2009, Sutton 2004, Thorston 2007, whittington 2009, Marks/Davis 2011
	Ownership and Satisfaction with system or water committee	Carter 1999, Davis 2012, Graciana 2012, Harvey 2003, 2004, 2007, Katsi 2007, Kleemeir 2000, Lockwood 2013, Narayan 1995, WSA 2013, Sugden 2001, Bhandari 2007, Chatterley 2011, Davis 2008, Mukherjee 2003, Gross 2001, Harvey 2007, 2004, IRC 2002, Hopkins 2004, Jones 2008, Lockwood 2003, Marks/Davis 2011, Prokopy 2005, 2008, Katz 1997, Mihelcic 2012, Schweitzer 2009, Mancinni, Harvey et al 2003, Abrams 1998, Smits Rojas 2012, Thorston 2007, Whittington 2008, 2009, Carter 1999
	Religious, cultural, Social believes (who should provide them with water, intercommunity competitions	Harvey 2007, CARE 2002, WEDC 1998, Bhattarai 2005, Armanios 2012, Bhandari 2007, Choguill 1996, Gine 2008, Godfrey 2013, Graciana 2012, Harvey 2004, 2007, Lockwood 2003, McConville 2006, Bartram 2009, Musonda 2004, Prokopy 2008, Schweitzer 2009, WSA 2013
	Proper (or improper use of the system)	Mukherjee 2003, Gross 2001, Parry-Jones 1999, Rojas 2012, Sugden 2001, Katsi 2007
External Support	Financial management	Lockwood 2012, Mandara 2013, Whittington 2008, WSA 2013, Haysom 2006, Harvey 2007
	Coordination, harmonization, alignment with others (govt., agencies, community), networked	Adank 2013, Chatterley 2011, Lockwood 2011, 2012, 2012, 2013, RWSN 2011, Katz 1997, Smits Rojas 2012, UNOM 2003.
	Type of organization	Lockwood 2003, 2011, Kleemeir 2010, RWSN 2011, Smits Rojas 2012
	Donor and/or funding Source	Chatterley 2011, Lockwood 2003, 2011, 2013, Foster 2013, Harvey 2010, 2004, 2010 Kaliba 2002, Bartram 2009, Silva 2013, Schweitzer 2009, Smith Rojas 2012,
	Community capacity building and training	Carter 2006, Kaliba 2002, Narayan 1995, Bartram 2009, Prokopy 2008, RWSN 2011, Shrikanth 2009, Katz 1997, Thorston 2007, Carter 1999, 2007, Chatterley 2012, Davis 2008, Foster 2013, Harvey 2004, 2007, 2010, Kleemeir 2000, Lockwood 2003, 2012 , Mackintosh 2003, Bartram 2009,

		Mukherjee 2003, Narayan 1995, Prokopy 2008, Katz 1997, Sugden 2001, Thorston 2007, Whittington 2008, 2009
Management	Training, education, behavior change, manuals, workshops, skills	Thorston 2007, Massoud 2008, Carter 1999, Carter 2007, DWA 2012 , Prokopy 2008, Taylor 2013, Chatterley 2011,2012, Davis 2008, Harvey 2010, Harvey 2004, Kleemeir 2000, Lockwood 2003, 2012, Mackintosh 2003, Bartram 2009, Mukherjee 2003, Katz 1997, Sugden 2001, Whittington 2008, Whittington Davis 2009, Godfrey 2009, Gross 2001, Hook 2006, Kaliba 2002, Katsi 2007, McConville 2006, Panthi 2006, RWSN 2011, Schweitzer 2009, Wiklinson 2007, WSA 2013, Gine 2008
	Tariff scheme, cost recovery, cost determination management, collection	Vasques 2013, Abramson 2011, Adank 2013, Alvarado 2009, Armanios 2012, Carter 1999, 2006, 2007, RWSN 2011, Chatterley 2011, Davis 2008, Hook 2006, Downs 2012, Foster 2013, Godfrey 2013, Graciana 2012, Harvey 2007, 2007, 2004, Haysom 2006, Jones 2008, 2012, Kaliba 2002, Kleemeir 2000, Lockwood 2003, 2011, 2012, 2012, Davis 2011, McConville 2006, Bartram 2009, Mukherjee 2003, Panthi 2006, Prokopy 2005, 2008, Katz 1997, Mihelcic 2012, Schweitzer 2009, Shaw 2012, Smits Rojas 2012, Sugden 2001, Thorston 2007, UNOM 2003, Wande 2010, WaterAid 2011, Whittington 1990, 2008, 2009, WSA 2013,
	Community-based management: operation and maintenance	Jimenez 2010, Haysom 2006, National Water Policy 2002, Jones 2012, Kaliba 2002, Shaw 2012, Silva 2013, Srikanth 2009, Wateraid 2003, Massoud 2008, Vasques 2013, Choguill 1996, Davis 2012, Whittington 2009
	Water committee structure, organization, meetings	Alvarado 2009, Carter 2006, Godfrey 2009, 2013, Graciana 2012, Lockwood 2012, Mukherjee 2003, Thorston 2007, Bhandari 2007, Bhattarai 2011, Harvey 2007, Harvey 2004, Hook 2006, Kaliba 2002, Kleemeir 2000, Bartram 2009, Musonda 2004, Panthi 2006, Katz 1997, Mihelcic 2012 Yanore 1995, Sugden 2001, Thorston 2007, WaterAid 2011, Carter 1999, Thorston 2007, Carter 2007, Kleemeir 2010, Lockwood 2003, Rojas Smits 2012, Prokopy 2008 , Shaw 2012, Thorston 2007, Whittington 2009
	Private operators, system managers, circuit riders	Godfrey 2013, Kleemier 2010, Lockwood 2012, Bartram 2009, Sugden 2001, World Bank Water Paper 2010, Lockwood 2012, Panthi 2006, Carter 1999, 2006, DWA 2012, Harvey 2004, 2007, 2010 Kleemeir 2010, Bartram 2009, RWSN 2011,
	Collaboration and coordination between stakeholders	DWA 2012, Lyer 2006, Kaliba 2002, Musonda 2004, Ramirez 2012, Srikanth 2009, Graciana 2012, Harvey 2004, 2007, 2010, Kleemeir 2000,
	Communication and information flow	Alvarado 2009, Carter 1999, Bartram 2009, Ramirez 2012, Smits Rojas 2012, Srikanth 2009
	Equity, social equity, gender involvement, key positions	Gine 2008, Graciana 2012, Gross 2001, Carter 2006, Gine 2008, Godfrey 2013, Hopkins 2004, Kaliba 2002, Mukherjee 2003, Schweitzer 2009, WHO 2002, Zoomers 2005, Alvarado 2009, Carter 1999, Chatterley 2011, Downs 2012, DWA 2012, Foster 2013, Graciana 2012, Harvey 2004, Haysom 2006, Lockwood 2003, Lockwood 2011, 2012, Marks/Davis 2011, Sugden 2001, WSA 2013
	Post-construction support, strengthening government and community	Alvarado 2009, Bhandari 2007, Bhattarai 2005, CARE 2000, WEDC 1998, Chatterley 2011, Choguill 1996, Mukherjee 2003, Foster 2013, Gine 2008, Graciana 2012, Harvey 2004, 2007, 2010, Jimenez 2010, Kaliba 2002, Lockwood/Schweitzer 2013, Lockwood 2003, 2011, 2013, Masduqui 2010, Bartram 2009, Musonda 2004, Pushpangadan 2008, Katz 1997, Schweitzer 2009, Kolesar 2004, Mathews 2005, Heat 2009, Smits Rojas 2012, WaterAid 2011, WHO 2002,

	Quality control	Lockwood 2003, 2011, 2013, Mackintosh 2003, RWSN 2011, Mihelcic 2012, Shaw 2012, Silva 2013, Whittington 2008, 2009, Wilkinson 2007, Davis 2008, Carter 1999, 2006, Davis 2008, Harvey 2007, Kleemeir 2000, Musonda, Prokopy 2008, WaterAid 2011, Gross 2001
	Skilled operator, skilled inspected, preventative, community care taker	Jones 2012, Adank 2013, Bhandari 2007, CARE 2000, WEDC 1998, Carter 1999, 2006 2007, Chatterley 2012, Chatterley 2011, , Mukherjee 2003, Downs 2012, Forester 2013, Gine 2008, Godfrey 2009, 2013, Graciana 2012, Hook 2006, Kleemeir 2010, Lockwood 2003, 2012, 2012, 13, Mandara 2013, McConville 2006, Bartram 2009, Musonda 2004, Panthi 2006, Parry-Jones 1999, Schweitzer 2009, Smits Rojas 2012, UNOM 2003, Wande 2010, WaterAid 2003, WaterAid 2011, Whittington 2008, Wilkinson 2007, Haysom 2006, Harvey 2004, Downs 2012, Adank 2013, Bhattarai 2005, Chatterley 2012, Mukherjee 2003, Foster 2013, Gine 2008, Godfrey 2013, Harvey 2007, 2010, Hook 2006, Jones 2012, Kaliba 2002, Kleemeir 2000,Lockwood 2003, Masduqui 2010, McConville 2006, Bartram 2009, Silva 2013, Sugden 2001, Sutton 2004, Thorston 2007, WaterAid 2003, WaterAid 2011, Whittington 2008, WSA 2013
	General management structure	Gine 2008, Kaliba 2002, Lockwood/Schweitzer 2013, Musonda 2004, Shaw 2012, Silvia 2013, Srikanth 2009, Thorston 2007, WSA 2013,
	Monitoring, evaluating, data management, reflection, water quality sampling, water metering, learning	Adank 2013, Alvarado 2009, Armanios 2012, Chatterley 2012, Downs 2012, Harvey 2007, Harvey 2010, Harvey 2004, Lyer 2006, Jimenez 2010, Jones 2012, Bartram 2009, Mukherjee 2003, Narayan 1995, RWSN 2011, Shaw 2012, Wande 2010, WaterAid 2011, WHO 2002, Wilkinson 2007, Zoomers 2005, Whittington 2008, Adank 2013, Mackintosh 2003, Lockwood 2013, Armanios 2012, Chatterley 2012, Haysom 2006, Kleemeir 2010, Lockwood 2013, Smits Rojas 2012, WaterAid 2011, Katsi 2007 Armanios 2012, Srinkanth 2009, Lockwood 2003, 2012, 2012, 2013, Mukherjee 2003, Carter 2006, RWSN 2011, Lockwood 2011, Zoomers 2005
	Quickness of repairs	Godfrey 2013, Mihelcic 2012, Carter 1999, Tynan & Kingdom 2002,
Financial	Financial sustainability, durability, management/Maintenance	Shrikanth 2009, Araminios 2012, Bhattarai 2005, Chatterley 2012, Mukherjee 2003, Gine 2008, Godfrey 2013, Graciana 2012, Harvey 2004, 2010, Hook 2006, Jimenez 2010, Jones 2008, Kleemeier 2010, Lockwood/Schweitzer 2013, Lockwood 2013, 2013, Bartram 2009, Panthi 2006, Parry-Jones 1999, Prokopy 2008, Pushpangadan 2008, Mihelcic 2012, Schweitzer 2009, Shaw 2012, Sugden 2001, UNOM 2003, WaterAid 2003, Whittington 2009, WSA 2013,
	Lifecycle costs and replacement funds	Lockwood 2012, Haysom 2006, Kaliba 2002, Katz 1997, Thorston 2007, Lockwood 2011, Shaw 2012, Mihelcic 2012, Bartram 2009. Harvey 2004, Lockwood 2003, 2012, Smits Rojas 2012, Whittington 2008
Environment & Infrastructure	Climate change/Conditions geography, ecology, topography	Sparks 2003, Srikanth 2009, Schweitzer 2009, Silva 2013, CARE 2000, WEDC 1998, McConville 2006, Lockwood 2003
	Energy (solar, grid, fuel): Reliability, affordability, availability/coverage	Jones 2008, Jones 2012, Schweitzer 2009, Silva 2013, Lockwood 2003 Prokopy 2008, Thorston 2007, Whittington 2009, Whittington 2008, Silva 2013

	Contamination, source protection	Massoud 2008, Chatterley2011, Gine 2008, Haysom 2004, Jones 2008, Mackintosh 2003, McConville 2006, Srikanth 2009, Whittington 2008 Alvarado 2009, Chatterley 2011, Katsi 2007, Lockwood 2011, Shaw 2012, Thorston 2007, WSA 2013, Armanios 2012, Bhattarai 2012, Graciana 2012, Harvey 2004, Jones 2010, Lockwood Schweitzer 2013, Masduqui 2010, Bartram 2009, Pushpangadan 2008, WaterAid 2011, CARE 2000, WEDC 1998, McConville 2006, Lockwood 2003, CARE 2000, WEDC 1998, Jones 2008, Jones 2012, Panthi 2006, Thorston 2007, WSA 2013, Graciana 2012, CARE 2000, WEDC 1998, DWA 2012, Foster 2013, Jones 2008, Lockwood 2003, 2013, McConville 2006, Panthi 2006, Shaw 2012, Thorston 2007, WSA 2013, Whitington 2008, Rietveld 2007, Silva 2013, Schweitzer 2009
	Management/ allocation (general)	Alvarado 2009, Chatterley 2011, Katsi 2007, Lockwood 2011, Shaw 2012, Thorston 2007, WSA 2013, Armanios 2012, Bhattarai 2012, Graciana 2012, Harvey 2004, Jones 2010, Lockwood Schweitzer 2013, Masduqui 2010, Bartram 2009, Pushpangadan 2008, WaterAid 2011
	Water quality, quantity, continuity	CARE 2000, WEDC 1998, Jones 2008, Jones 2012, Panthi 2006, Thorston 2007, WSA 2013, Graciana 2012, CARE 2000, WEDC 1998, DWA 2012, Foster 2013, Jones 2008, Lockwood 2003, 2013, McConville 2006, Panthi 2006, Shaw 2012, Thorston 2007, WSA 2013
Technology Construction & Materials	Cost of technology	Jones 2008, Lockwood 2011, Masduqui 2010, Harvey 2004, RWSN 2011, Shweitzer 2009, Mancinni 2004
	Distance to municipality or major city centers	Katsi 2007, Thorston 2007, Bhandari 2007, Carter 2006, Davis 2008, Foster 2013, Armanios 2012, Lockwood 2003, Prokopy 2008, Whittington 2008, 2009,
	Standards components, construction	Harvey 2004, Lockwood 2003, 2011, Bartram 2009, Sutton 2004, Choquill 1996, Lockwood 2013
	Spare parts, affordable materials, tools	Carter 2007, Kaliba 2002, Massoud 2008, Adank 2013, Carter 1999, Chatterley 2012, Downs 2012, Lyer et al 2006, DWA 2012, Gine 2008, Godfrey 2009, 2013, Harvey 2006, 2010, 2004, Haysom 2006, Jones 2012, Kaliba 2002, Kleemeir 2010, Lockwood 2003, 2012, 2012, Masduqui 2010, Bartram 2009, Musonda 2004, Prokopy 2008,Schweitzer 2009, Shaw 2012, Sugden 2001, Sutton 2004, WaterAid 2003, 2011, Whittington 2008, WSA 2013,
	Quality construction, materials	Gine 2008, Jones 2012, Graciana 2012, Panthi 2006, Bhattarai 2005, Carter 2006, Chatterley 2012, RWSN 2011, Katz 1997, Silva 2013, WaterAid 2011
	Project age	Marks/Davis 2011, Katz 1997, Mihelcic 2012, Whittington 2008, 2009, Massoud 2008, Carter 2006, Davis 2008, Foster 2013, Jones 2008, Prokopy 2008, Thorston 2008,
	System tech. type: centralized, POU, level of service going to point or household	Carter 2006, Jones 2008, Lockwood 2003, Katz 1997 ,Shaw 2012, Rojas 2012, Foster 2013, Katsi 2007, Masduqui 2010, Prokopy 2008, WHO 2002, World Bank 2010
	Appropriateness of technical planning, design, construction, technology	Chatterley 2011, Graciana 2012, Lockwood 2003, Narayan 1995, Parry-Jones 1999, Thorston 2007, Bhandari 2007, Bhattarai 2005, Chatterley 2012, Downs 2012, Lyer 2006, Gine 2008, Godfrey 2013, Harvey 2004, Haysom 2006, Kleenmier 2000, 2010, Lockwood/Schweitzer 2013, Lockwood 2003, 2011, 2013, Mackintosh 2003, McConville 2006, Bartram 2009, Musonda 2004, Prokopy 2008, Pushpangadan 2008, Rietveld 2007, Smits Rojas 2012, Shaw 2012, Sutton 2001, WaterAid 2003,2011, WSA 2013

System Functionality	Quantity meeting the demand of the community	Lockwood 2012, 2013, Mukherjee 2003, Rietveld 2007, Rojas 2012, Sugden 2001, Jones 2012, Lockwood 2012, Rietveld 2007, Adank 2013, Chatterley 2011, Katsi 2007, RWSN 2011, Schweitzer 2009, Panthi 2006
	Quality: (fecal coliforms, nutrients, taste, color, etc.)	Lockwood 2013, Rojas 2012, Sugden 2001, Adank 2013, Chatterley 2011, Mukherjee 2003, Foster 2013, Howard 2003, Jones 2008, Katsi 2007, Lockwood 2012, Mackintosh 2003, Panthi 2006, Pushpangadan 2008, Rietveld 2007, RWSN 2011, Srikanth 2009, Graciana 2012,
	Distance from tap to house	Adank 2013, Bhandari 2007, Hook 2006, Hopkins 2004, Kasti 2007, Lockwood 2011, 2012, 2012, 2013, Prokopy 2007, 2008, Rietveld 2007, RWSN 2011, Katz 1997, Sutton 2004, Thorston 2007, Sugden 2001, Schweitzer 2009
	Operation, flow	Bhandari 2007, Bhattarai 2005, Carter 1999, Graciana 2012, Harvey 2007, 2004, Hook 2006, Kaliba 2002, Lockwood 2011, 2013, Mukherjee 2003, Perry-Jones 1999, Rojas 2012, Whittington 2008, Panthi 2006,
	Reliability and continuity	Lockwood 2011, 2012,2013, Davis 2011, Mihelcic 2012, Rojas 2012, Thorston 2007, World Bank 2010, Adank 2013, Sugden 2001, Rietveld 2007, Hook 2006, Katsi 2007, Schweitzer 2009, Adank 2013, Jones 2008, Kaliba 2002, Panthi 2006, RWSN 2011,
	Equity	Bhattarai 2005, Mukherjee 2003, Graciana 2012, Gross 2001, Harvey 2007 Jones 2008, Prokopy 2005, Wande 2010, Jimenez 2010, Katsi 2007, Lockwood 2011, 2013, Bartram 2009, Panthi 2006, WaterAid 2003, WSA 2013, Schweitzer 2009, Smits Rojas 2012, RWSN 2011

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APPENDIX B: DELPHI AND CROSS IMPACT STUDY

This appendix presents the data collection tools and findings from the two-round expert Delphi polarity analysis and cross impact study, showcased in Chapter 2. Data collection tools are presented as two example screenshots of the online Qualtrics forms that were used to engage experts in the Delphi and cross impact survey (Figure B-1 and B-2, respectively); as the consensus results for each Delphi Round (Table B-1); and as the raw cross impact scores for each factor (Table B-2).

EXAMPLE QUALTRICS FORMS

Expert panelists participated in the Delphi and cross impact survey using the online Qualtrics forms presented below. These are not the complete forms, but are examples of how panelists interfaced with the study materials.

Figure B-1: Delphi polarity analysis

Please select the polarity of influence of each of the 7 Factors on rural water System Functionality. How might each Factor influence Water System Functionality?

	INFLUENCE OF EACH FACTOR ON FUNCTIONALITY			
	+: Increase in the Factor causes an INCREASE in System Functionality	0: The Influence is small or unimportant	-: Increase in the Factor causes a DECREASE in System Functionality	I Don't Know
Government				
Community				
External Support				
Management				
Financial				
Tech. Construction & Materials				
Environment & Energy				

Figure B-2: Cross impact survey

Please indicate the strength of influence between the following Capacities/Water System influences. The strengths will be indicated numerically as: 0 = Non-Existent, 1 = Weak, 2 = Medium, and 3 = Strong. A capacity on itself (e.g. Government on Government), should be filled in with a 0. Once you have filled out this matrix, hit the "submit" button and Round 3 will be complete. A repeat of the simplified example for how to fill out the matrix is shown below:

		INFLUENCED		
	Factor	A	B	C
INFLUENCING	A	--	A on B	A on C
	B	B on A	--	B on C
	C	C on A	C on B	--

	Government	Community	Ext. Supp.	Management	Financial	Enviro & Energy	Tech, Const & Mat	Wat. Sys. Funct
Government								
Community								
Ext. Support								
Management								
Financial								
Enviro & Energy								
Tech, Const & Mat								
Wat. Sys. Funct.								

DELPHI RESULTS

For each of the two Delphi rounds, consensus on a particular influence polarity was ascertained using the Average Percentage Majority Opinion (APMO). Table B-1 presents the consensus results for each round based on these consensus criteria.

Table B-1: Delphi Round 1 and 2 results

Influence Number	Factor	Influence Description	Round 1 +	Round 1 0	Round 1 -	Round 1 Maj. %	Round 1 APMO	Round 2 +	Round 2 0	Round 2 -	Round 2 Maj. %	Round 2 APMO	Final Consensus?
1		Gov - Func	21	2	0	91		------CONSENSUS------					yes
2		Com - Func	22	1	0	96		------CONSENSUS------					yes
3		Ext - Func	16	5	1	73		17	4	1	77		no
4	Water System Functionality	Man - Func	21	1	0	95	90	------CONSENSUS------				82	yes
5		Fin - Func	21	1	0	95		------CONSENSUS------					yes
6		E&E - Func	18	3	0	86		19	3	0	86		yes
7		TCM - Func	20	1	1	91		------CONSENSUS------					yes
8		Func - Gov	7	11	1	58		7	15	0	68		no
9		Func - Com	18	3	0	86		------CONSENSUS------					yes
10		Func - Ext	3	13	4	65		2	18	2	82		yes
11	Water System Functionality	Func - Man	13	7	0	65	67	16	6	0	73	72	yes
12		Func - Fin	18	3	0	86		------CONSENSUS------					yes
13		Func - E&E	6	10	2	56		7	15	0	68		no
14		Func - TCM	10	9	0	53		7	15	0	68		no
15		Gov - Com	15	4	2	71		18	2	2	82		yes
16		Gov - Ext	9	7	5	43		9	9	4	41		no
17	Government	Gov - Man	20	0	1	95	72	------CONSENSUS------				55	yes
18		Gov - Fin	18	4	0	82		------CONSENSUS------					yes
19		Gov - E&E	15	6	0	71		13	8	1	59		yes
20		Gov - TCM	15	6	0	71		17	5	0	77		yes
21		Com - Gov	5	13	3	62		4	18	0	82		yes
22		Com - Ext	6	10	6	45		7	13	2	59		yes
23	Community	Com - Man	19	1	0	95	65	------CONSENSUS------				50	yes
24		Com - Fin	18	4	0	82		------CONSENSUS------					yes
25		Com - E&E	9	11	0	55		11	11	0	50		no
26		Com - TCM	10	11	0	52		13	9	0	59		yes
27		Ext - Gov	12	3	6	57		------CONSENSUS------					yes
28		Ext - Com	11	4	6	52		13	6	3	59		no
29	External Support	Ext - Man	10	6	4	50	53	18	3	1	82	65	yes
30		Ext - Fin	13	5	3	62		------CONSENSUS------					yes
31		Ext - E&E	9	10	1	50		9	12	1	55		no
32		Ext - TCM	12	7	2	57		-------CONSENSUS-----					yes
33		Man - Gov	7	12	0	63		6	16	0	73		no
34		Man - Com	14	5	0	74		------CONSENSUS------					yes
35	Management	Man - Ext	7	11	2	55	70	4	17	1	77	78	no
36		Man - Fin	21	0	0	100		------CONSENSUS------					yes
37		Man - E&E	12	6	1	63		17	5	0	77		no
38		Man - TCM	12	6	1	63		18	3	1	82		yes
39		Fin - Gov	9	9	1	47		15	7	0	68		yes
40		Fin - Com	20	1	0	95		------CONSENSUS------					yes
41	Financial	Fin - Ext	8	8	4	40	56	10	9	3	45	58	no
42		Fin - Man	20	0	0	100		------CONSENSUS------					yes
43		Fin - E&E	9	8	1	50		13	9	0	59		yes
44		Fin - TCM	16	3	0	84		------CONSENSUS------					yes
45		E&E - Gov	7	10	1	80		------CONSENSUS------					yes
46		E&I - Com	13	5	2	55		------CONSENSUS------					yes
47	Environment & Energy	E&E - Ext	3	12	3	70	55	------CONSENSUS------				52	yes
48		E&E - Man	13	5	1	68		------CONSENSUS------					yes
49		E&E - Fin	11	5	1	52		10	12	0	55		yes
50		E&E - TCM	9	8	1	47		11	11	0	50		no
51		TCM - Gov	4	16	0	56		5	17	0	77		yes
52		TCM - Com	9	11	0	65		------CONSENSUS------					yes
53	Technology, Construction & Materials	TCM - Ext	5	14	1	67	59	------CONSENSUS------				68	yes
54		TCM - Fin	13	6	0	68		------CONSENSUS------					yes
55		TCM - Man	11	10	0	65		------CONSENSUS------					yes
56		TCM - E&E	9	9	1	50		9	13	0	59		no

CROSS IMPACT RESULTS

Within the cross impact survey, each expert panelist indicated the strength of influence between each of the eight sustainability factors described above in Appendix A. Below are the raw influence scores that were used for loop dominance ranking described in Chapter 2.

Table B-2: Cross impact analysis raw data (Gov = Government, Com = Community, Ext = External Support, Man = Management, Fin = Finances, E&E = Environment & Energy, TCM = Technology, Construction & Materials, WSF = Water System Functionality)

GOVERNMENT							
GOV	**COM**	**EXT**	**MAN**	**FIN**	**E&E**	**TCM**	**WSF**
0	2	3	3	3	1	3	2
0	2	0	2	1	2	1	2
0	1	3	2	2	1	1	2
0	3	3	2	3	3	3	3
0	2	2	3	3	1	3	3
0	1	3	2	1	1	1	1
0	1	1	1	1	2	1	1
0	3	1	1	1	3	2	1
0	3	2	2	3	2	2	2
0	3	0	3	3	2	2	2
0	3	2	2	1	0	1	2
0	2	1	2	2	3	2	2
0	1	2	1	1	2	2	2
0	3	1	2	3	3	3	3
0	3	0	2	1	3	3	3
0	2	1	2	1	2	1	2
0	3	2	3	3	2	2	3
0	2	0	2	2	3	2	2
0	3	3	3	3	2	2	2
COMMUNITY							
GOV	**COM**	**EXT**	**MAN**	**FIN**	**E&E**	**TCM**	**WSF**
2	0	1	1	1	1	1	2
0	0	0	2	2	0	1	2
0	0	0	3	2	3	2	3
0	0	1	3	2	1	2	2
2	0	2	1	2	2	1	2
2	0	2	2	2	1	1	2
1	0	1	3	2	1	2	3
1	0	2	2	3	1	2	3
1	0	0	2	2	1	2	2
2	0	2	2	3	2	1	2
2	0	2	3	2	2	2	3

1	0	0	3	1	2	0	2
3	0	3	3	3	1	1	3
1	0	2	2	2	1	1	3
0	0	1	2	2	1	2	2
3	0	1	3	2	2	2	2
1	0	1	2	3	2	1	3
0	0	1	2	1	2	1	3
2	0	1	2	1	1	1	1
EXTERNAL SUPPORT							
GOV	**COM**	**EXT**	**MAN**	**FIN**	**E&E**	**TCM**	**WSF**
3	3	0	3	2	1	2	2
1	0	0	2	3	0	2	0
2	2	0	2	2	2	2	2
2	1	0	3	2	1	3	2
3	2	0	2	3	3	3	3
2	2	0	1	3	1	2	2
0	3	0	3	3	2	2	3
1	2	0	2	2	1	3	2
2	3	0	2	1	3	3	1
2	3	0	2	1	1	1	1
1	1	0	0	2	1	3	2
1	3	0	3	2	2	2	3
2	2	0	3	2	2	2	3
1	2	0	2	2	1	2	2
2	3	0	2	2	1	2	2
1	2	0	1	1	1	1	1
2	1	0	1	1	1	1	1
1	2	0	2	1	2	2	2
2	2	0	2	2	2	2	2
MANAGEMENT							
GOV	**COM**	**EXT**	**MAN**	**FIN**	**E&E**	**TCM**	**WSF**
2	2	1	0	2	2	2	3
0	1	0	0	1	0	2	3
0	2	0	0	2	1	2	3
0	2	1	0	3	2	3	3
1	1	1	0	2	3	3	3
1	1	2	0	2	2	2	3
0	3	2	0	3	2	2	3
1	2	2	0	2	1	2	2
0	0	0	0	2	1	1	3
2	3	1	0	3	3	3	3
1	3	1	0	3	2	3	3
1	2	0	0	2	2	2	2
2	3	2	0	3	1	1	3
0	2	2	0	2	1	3	3
1	2	2	0	2	2	1	3

3	2	1	0	2	2	2	2
1	1	2	0	1	1	1	3
0	0	0	0	0	2	1	2
2	2	1	0	3	3	3	3
FINANCIAL							
GOV	**COM**	**EXT**	**MAN**	**FIN**	**E&E**	**TCM**	**WSF**
3	2	3	3	0	2	2	31
2	2	0	2	0	2	2	2
1	2	1	1	0	2	2	3
0	1	1	3	0	1	3	3
3	2	2	3	0	3	3	3
2	2	2	3	0	1	1	3
0	1	2	2	0	2	2	2
1	3	2	2	0	1	2	3
0	0	0	2	0	0	2	3
1	2	1	3	0	1	2	3
2	3	2	3	0	1	2	3
3	3	0	3	0	1	2	3
1	3	3	3	0	1	1	3
1	3	2	2	0	1	2	3
2	3	2	1	0	1	2	2
3	2	1	3	0	3	3	3
2	3	1	3	0	1	1	3
0	1	0	2	0	1	1	2
3	3	2	2	0	2	3	3
ENVIRONMENT & ENERGY							
GOV	**COM**	**EXT**	**MAN**	**FIN**	**E&E**	**TCM**	**WSF**
1	2	1	1	3	0	3	3
0	2	0	3	2	0	0	3
0	1	0	1	1	0	0	2
0	2	0	1	1	0	1	2
1	2	2	0	2	0	0	2
1	1	1	1	1	0	2	3
0	2	1	1	2	0	1	3
0	2	1	2	1	0	1	2
1	2	2	3	0	0	2	3
1	2	1	1	1	0	1	3
1	2	2	2	2	0	3	3
0	0	0	3	1	0	0	3
0	2	2	2	1	0	1	2
1	2	2	1	1	0	2	2
1	2	1	1	1	0	2	2
3	3	1	2	2	0	2	2
0	2	0	2	1	0	1	2
0	0	0	1	0	0	1	3
2	2	2	2	1	0	1	2

TECHNOLOGY, CONSTRUCTION & MATERIALS							
GOV	COM	EXT	MAN	FIN	E&E	TCM	WSF
1	2	1	1	2	2	0	2
0	0	0	3	0	0	0	3
0	1	0	1	1	0	0	2
0	1	1	1	1	1	0	2
0	0	1	0	2	2	0	3
1	1	1	2	1	3	0	3
0	1	1	2	2	1	0	3
1	2	2	2	1	1	0	2
0	2	0	2	3	0	0	3
1	3	2	3	3	1	0	3
1	2	3	2	2	2	0	3
0	0	0	3	2	1	0	3
1	1	1	2	2	1	0	2
1	2	2	3	2	1	0	2
1	2	2	1	1	2	0	2
3	1	1	3	3	1	0	3
2	2	0	1	2	1	0	2
0	0	0	2	0	1	0	3
2	2	1	2	3	2	0	2
WATER SYSTEM FUNCTIONALITY							
GOV	COM	EXT	MAN	FIN	E&E	TCM	WSF
1	3	2	2	2	0	1	0
0	2	0	1	2	0	0	0
0	3	0	2	2	0	0	0
1	3	1	3	3	1	2	0
0	3	2	0	3	1	0	0
1	1	1	2	1	3	3	0
1	3	3	3	3	1	1	0
1	3	3	2	2	1	2	0
1	3	2	2	2	2	2	0
2	3	1	2	2	2	1	0
2	3	2	2	3	2	2	0
2	2	0	2	2	2	0	0
2	3	3	3	3	2	2	0
1	2	2	3	3	1	3	0
1	3	3	2	2	2	2	0
3	2	1	2	3	3	3	0
2	3	0	3	3	1	1	0
0	1	0	1	0	2	1	0
2	3	1	3	2	2	2	0

APPENDIX C: CASE STUDY MATERIALS AND ANALYSIS

This appendix presents the materials used to perform interviews with community water committee members for the Terrabona and Darío, Nicaragua, case study presented in Chapter 4. It subsequently presents the interview and observation guide used by Jeff Walters and Tim Roberts (Table C-1 English, and C-2 Spanish); the raw coding used in the qualitative analysis of the transcribed interviews (Table C-3); and lastly, the results from binary factor quantification for both coded themes (Tables C-4 and C-6 for Darío and Terrabona, respectively) and aggregated factors (Table C-5 and Table C-7 for Darío and Terrabona, respectively).

INTERVIEW GUIDE

The interview guide below was created based on the factors identified in the literature review, conversations with organizational leaders involved in rural water infrastructure in Nicaragua, and the author's own experience working as a water practitioner.

Table C-1: Interview guide (English)

Factor	Topic	Question Code	Question
Water System	Origin of water system	WS1	Do you have a water system? If so who installed your water system?
	Well	WS2	What kind of water system do you have?
	Well with India II		
	Electric pump		
	Gravity		
	System age	WS3	How old is your water system
	System story	WS4	Have there been other water systems installed in this community? If so, can you tell me the history?
Community Water Committee	# Meetings (activity)	CAPS1	Does this community have a water committee? If so, how often do you meet?
	System maintenance	CAPS2	How often do you do maintenance on the water system?
	Chlorination	CAPS3	Is the water system chlorinated? If not, do you add chlorine to you water? If so, how often?
	Legalized in	CAPS4	Is the water committee registered with the

	municipality		government?
	Gender	CAPS5	How many women are on the water committee?
Government	Visits/ Communication	GOV1	How often does the government visit your community? How often do you communicate with the government?
	Trainings	GOV2	Does the government continue to offer trainings with your water system?
	Technical support	GOV3	Does the government help with maintenance of the water system?
	Financial support	GOV4	Does the government help fund maintenance of the water system?
External Support	Organization	EXT1	Are you currently being helped by an organization? If so, who?
	Visits	EXT2	How often does the organization visit your community? How often do you communicate with the organization?
	Trainings	EXT3	How often does the organization have trainings for proper use, and maintenance of the water system?
	Technical support	EXT4	Does the organization help with maintenance of the water system?
	Financial support	EXT5	Does the organization help fund maintenance of the water system?
Community Behavior	Meeting	CB1	How often are there community meetings?
	Attendance	CB2	When there is a community meeting, what percentage of the community usually attends?
	Tariff Payment	CB3	Does the community pay a tariff for their water system? If so, how much? Does everyone pay
	Unity/Collaboration	CB4	Have there been any conflicts in the community regarding the water system?
	Priorities (demand)	CB5	What are the greatest needs of your community? (if water) are there alternative water sources available?
Community Demographics & Population	Education	CD1	What is the average level of education in the community
	Political party	CD2	What political party is this community associated with?
	Population	CD3	How many houses are in this community?
Income of Community	Job continuity	IC1	What is the main income for the community?
	Monthly income	IC2	More or less, what is the average household income?
Financial	Tariff	FIN1	Does the community pay a tariff for their water system? If so, how much?
	Account	FIN2	Does the community have a savings account dedicated towards the water system?
	Tariff $$ to pay for proper operation	FIN3	Is there enough money to pay for all operation of the system?
	Tariff $$ to pay for	FIN4	Is there enough money to pay for all maintenance of

	maint		the system?
	Tariff $$ for repairs	FIN5	Is there enough money to pay for all repairs of the system?
Land Owner	Source	LO1	Does the community own the water source?
	Conflicts	LO2	If land now owned: Are there any issues with the land owner?
	Area near source	LO3	Are their farms in the watershed?
Electricity	Availability	E1	Is electricity available in your community?
	Continuity	E2	Are there ever times when the electricity is not working?
	Cost	E3	Is the cost of the electricity affordable?
Road Condition	Pass-ability	RC1	Are there times in the year when the road to (Terrabona or Darío) was not passable?
Functionality	Taste	F1	Do you have any problems with the taste of the water?
	Quantity	F2	Is the amount of water enough for the needs of the community?
	Continuity	F3	Are there ever times when the water system was not working?
	Distance	F4	How far do you have to walk to get water?
Water System (OBS)	Water cloudy? (yes or no)	OBWS1	
	Wear of the system (corrosion, concrete decay…etc)?	OBWS2	
	Cleanliness around system	OBWS3	
Water Resources (OBS)	Fenced	OBWR1	
	Animals	OBWR2	
	Plantation	OBWR3	
	Rainy season	OBWR4	

Table C-2: Interview guide (Spanish)

Question Code	Question (Spanish)
WS1	¿Tiene un sistema de agua? Si es así quien instaló su sistema de agua?
WS2	¿Qué tipo de sistema de agua Tiene en su comunidad?
WS3	¿Cuántos años tiene su Sistema de agua?
WS4	¿Ha habido otros sistemas de agua instalados en esta comunidad? Si es así, ¿me puede decir la historia?
CAPS1	¿Tiene la comunidad un comité de agua? Si es así, ¿con qué frecuencia se reúnen?
CAPS2	¿Con qué frecuencia lo hace el mantenimiento del sistema de agua?
CAPS3	¿Se clora el sistema de agua? Si no, ¿están la gente echando cloro para que el agua sea limpia? Si es así, ¿con qué frecuencia?
CAPS4	¿El comité de agua registrado con el gobierno?
CAPS5	¿Cuántas mujeres están en el comité de agua?
GOV1	¿Con qué frecuencia el gobierno visita su comunidad? ¿Con qué frecuencia se comunica con el gobierno?
GOV2	¿El gobierno continuará ofreciendo entrenamientos con su sistema de agua?
GOV3	¿Está el gobierno ayudándoles con el mantenimiento del sistema de agua?
GOV4	¿Está el gobierno ayudándoles financiar el mantenimiento del sistema de agua?
EXT1	¿Está la comunidad recibiendo apoyo por una organización con su systema de agua? Si es así, ¿quién?
EXT2	¿Con qué frecuencia esta el organización visitando su comunidad? ¿Con qué frecuencia se comunica con la organización?
EXT3	¿Con qué frecuencia tiene la organización capacitaciones para el uso correcto y el mantenimiento del sistema de agua?
EXT4	¿La organización ayuda con el mantenimiento del sistema de agua?
EXT5	¿La organización de mantenimiento de la ayuda del fondo del sistema de agua?
CB1	¿Con qué frecuencia hay reuniones de la comunidad?
CB2	¿Cuándo hay una reunión de la comunidad, ¿qué porcentaje de la comunidad por lo general asiste?
CB3	¿La comunidad paga una tarifa por su sistema de agua? Si es así, ¿cuánto? ¿Paga todos?
CB4	¿Ha habido conflictos en la comunidad en relación con el pago? ¿Hay personas que no pagan? ¿Si es asi, cuantos casas?
CB5	¿Cuáles son las mayores necesidades de su comunidad? (Si el agua) ¿existen fuentes de agua alternativas disponibles?
CD1	¿Cuál es el nivel promedio de educación en la comunidad?

CD2	¿Qué partido político está asociado con esta comunidad?
CD3	¿Cuántas casas se encuentran en esta comunidad?
IC1	¿Cuál es la principal fuente de ingresos para la comunidad?
IC2	Más o menos, ¿cuál es el ingreso promedio de los hogares?
FIN1	¿La comunidad paga una tarifa por su sistema de agua? Si es así, ¿cuánto?
FIN2	¿Tiene la comunidad una cuenta de ahorros dedicada hacia el sistema de agua?
FIN3	¿Hay suficiente dinero para pagar por todo el funcionamiento del sistema?
FIN4	¿Hay suficiente dinero para pagar por todo mainenance del sistema?
FIN5	¿Hay suficiente dinero para pagar todas las reparaciones del sistema?
LO1	¿La comunidad es el dueno la fuente de agua?
LO2	Si la tierra ahora propiedad: ¿Hay algún problema con el dueño del terreno?
LO3	¿Hay fincas alrededor de la fuente?
E1	¿Hay electricidad (luz) en su comunidad?
E2	¿Hay algunas veces cuando la electricidad no está funcionando?
E3	Es el costo de la electricidad asequible?
RC1	¿Hay momentos en el año en que el camino de la (Terrabona o Darío) no está en servicio?
F1	¿Tiene algún problema con el sabor del agua?
F2	¿Es la cantidad de agua suficiente para las necesidades de la comunidad?
F3	¿Hay alguna vez momentos en que el sistema de agua no funcionaba?
F4	¿Que tan lejos tiene que caminar para conseguir agua?

CODING DICTIONALRY FOR QUALITATIVE ANALYSIS

Water committee member interviews were transcribed and coded to identify and classify themes, or reasons for why a community water system was or was not functioning. Below are the raw codes that were used to develop the factors used in Chapter 4.

Table C-3: Coding dictionary

Code	Sources	References	Definition
Climate	23	34	Informant reference to climate change influencing area
Com - Alternative sources	23	31	Use of more than one water source for drinking
Com - CAPS	45	90	Existence of a water committee
Com - Chlorination	23	29	Use of chlorine to disinfect

Com - Conflicts	18	31	Issues within the community regarding tariff collection
Com - Demand (priority, necessity...etc)	16	20	Community demand present to have clean water
Com - Economy	26	41	Community economic status
Com - Improvements	1	1	Community mentioned initiative to make system. Improvements
Com - Initial payment	10	11	Community members pay initial funds for water system
Com - Institutional involvement	55	215	Existence of institutional involvement (i.e., NGO)
Com - Maintenance	24	35	Community took initiative to repair system
Com - Meetings	7	8	Community mentioned community meetings as important
Com - Monitoring and evaluation, reporting	1	1	Community involved in monitoring and evaluation
Com - organization	17	20	Community appeared organized (holding meetings 1x/mo)
Com - Reforestation	12	15	Community indicated involvement with reforestation near the source
Com - Religion	1	1	Religion of community
Com - Repairs	22	33	Community initiative to make repairs
Com - Savings	28	44	Existence of savings for O&M
Com - Sweat equity	9	9	Community put their own labor into implementing water system
Com - Tariff	46	88	Monthly user fee
Com - Topography	1	1	Topography of the community influencing water availability
Com - Training	2	3	Community in charge of holding trainings
Com - Use	8	13	Community members using water source responsibly
Com - Women in leadership	1	1	Women in leadership (water committees)
Energy	18	20	Availability of electrical energy
Energy costs	9	17	Cost of Electrical Energy
Energy shortages	12	15	Reliability of electrical energy
Environmental resources	16	24	Water resources in general
Failure mode	5	6	Direct reference to the failure mode of the system
Functionality - Distance	9	11	Distance Users have to walk
Functionality - Equity	10	12	Availability of services to all people in community
Functionality - Quality	18	25	Quality of the water based on past MINSA tests
Functionality - Quantity	12	15	Interviewee opinion on quantity of water
Functionality - Reliability	18	26	Reliability of the water system
Functionality - Rhortage	29	43	
Functionality - Taste	1	1	Reference to taste of water.
Government	45	107	Involvement of government with water project
Gringo bias	2	3	Any obvious solicitation of interviewer for money
Historical trend	32	45	References to historical trends in functionality
Land ownership	32	53	Whether the community owns the land or not
Law and rights	18	33	Whether the community or water committee has rights to water

Meter	9	14	Water meters used in communities to regulate use
Natural disasters	3	3	Reference to natural disasters (i.e., Hurricane Mitch)
Political party	3	7	References to the political party of the community affecting government involvement
Resilience	2	4	Instances where the community was resilient to issues that affected water system
Road conditions	31	50	Whether committee members could leave the community for spare parts
Sectors	11	27	Reference to sectorization in communities
Sickness	2	2	Reference to sickness (related to water quality above)
System - Age	41	58	Age of the system
System - Current state	9	14	Current state of functionality of the water system
System - Source Protection	26	38	Whether or not the source is protected
System - Type	48	81	The type of system that is implemented (well, gravity-fed..etc)
TCM	48	99	Availability of materials (supply chain)
Technician	15	15	The designation of a skilled technician to take care of system O&M
Transportation	13	13	Availability of transportation to leave the community
Willingness to pay	1	1	Willingness for community to put forward upfront system costs

FACTOR QUANTIFICATION

Table C-4: Darío Themes

Community	Qual	Quant	Cont	Conf	Org	Clean	Fenc	Forr	Gov	Com.	Roads	Tar	Sav	Mat	ApTec	Ex Sup
Candelaria	no	no	no	no	no	no	no	no	no	no	yes	no	no	yes	yes	yes
Casas Viejas	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	no	yes	yes	yes	yes	yes
El Achote	no	no	yes	no	no	yes	no	yes	no	no	no	no	no	yes	yes	no
El Bacacan	no	no	no	yes	no	yes	no	no	no	no	no	no	no	no	no	no
El Carbonal	yes	no	yes	yes	yes	no	yes	no	no	no	yes	yes	yes	yes	yes	yes
El Carmen	no	no	yes	yes	no	yes	no	no	no	no	no	no	no	no	yes	yes
El Chaguite	no	yes	yes	no	no	yes	no	yes	yes	no	no	no	no	no	yes	yes
El Cristal	no	no	no	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	yes
El Guineo	yes	no	no	yes	no	no	no	no	yes	no	yes	yes	no	no	yes	no
El Hato	no	no	no	no	yes	no	no	yes	no	yes	no	yes	yes	yes	yes	yes
El Jícaro	no	no	no	no	yes	no	no	yes	no	yes	no	yes	yes	no	yes	yes
El Jobo	no	yes	yes	yes	yes	no	yes	no	yes	yes	no	yes	yes	yes	no	yes
El Pavón	yes	yes	yes	yes	no	no	no	no	yes	yes	yes	no	no	no	no	yes
El Prado	yes	no	yes	yes	yes	no	yes	yes	yes	yes	no	yes	no	no	yes	no
El Sisteo	no	yes	yes	yes	no	no	yes	no	yes	no	no	no	no	yes	yes	no
Guapinol	no	no	no	no	yes	no	no	yes	yes	yes	no	yes	yes	yes	yes	yes
El Zarzal	no	no	yes	no	no	yes	yes	no	no	no	no	yes	yes	no	yes	no
La Ceibita	no	no	yes	no	yes	no	no	no	yes	yes	no	yes	yes	yes	yes	yes
La Cruz	yes	no	yes	yes	no	no	no	no	no	no	no	no	no	yes	yes	yes
La Flor	yes	yes	no	no	yes	no	no	yes	no	yes	no	yes	yes	no	yes	yes
Las Mesas	no	no	no	no	yes	no	yes	yes	yes	yes	yes	yes	yes	no	no	yes
Las Palmas	no	no	no	yes	no	yes	no	no	no	no	no	no	no	no	yes	no
Las Pozas	no	yes	yes	no	no	no	no	yes	no	no	yes	no	no	no	yes	no
Los Capules	yes	yes	no	no	yes	no	no	yes	no	no	yes	yes	yes	no	yes	no
Los Cerritos	yes	yes	yes	yes	yes	no	no	yes	no	yes	no	yes	yes	yes	yes	yes
Sabana Verde	no	no	yes	yes	yes	no	yes	no	yes	yes	no	yes	yes	yes	no	yes
San Esteban	no	yes	yes	yes	no	yes	yes	no	yes	no	yes	no	no	no	no	no
Valle San Juan	yes	yes	yes	no	no	no	yes	yes	no	yes	no	yes	yes	yes	no	yes
San Lucia	yes	yes	no	no	yes	no	no	yes	no	yes	yes	yes	yes	yes	yes	yes
El Llano	no	yes	no	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no
Tamalapa	no	yes	no	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no
El Tempisque	no	no	no	no	yes	no	no	yes	yes	yes	no	yes	yes	yes	yes	yes
Veracruz	yes	yes	yes	yes	yes	no	yes	no	yes	yes	no	yes	yes	yes	no	yes

Table C-5: Darío Factors

Community	Government	Ext. Supp.	Finances	Manage	Infra	Wat. Res.	Wat. Sys. Funct	Tech.
no	no	yes	no	no	yes	no	no	yes
yes	yes	yes	yes	yes	no	yes	yes	yes
no	no	no	no	no	no	yes	no	yes
no	no	no	no	no	no	no	no	no
no	no	yes	yes	no	yes	no	yes	yes
no	no	yes	no	no	no	no	no	no
no	yes	yes	no	no	no	yes	no	no
yes	yes	yes	yes	yes	yes	yes	no	no
no	yes	no	yes	no	yes	no	no	no
yes	no	yes	yes	yes	no	yes	no	yes
yes	no	yes	yes	yes	no	yes	no	no
no	yes	yes	yes	yes	no	no	no	yes
no	yes	yes	no	yes	yes	no	yes	no
no	yes	no	yes	yes	no	yes	yes	no
no	yes	no	no	no	no	no	no	yes
yes	yes	yes	yes	yes	no	yes	no	yes
no	no	no	yes	no	no	no	no	no
yes	yes	yes	yes	yes	no	no	no	yes
no	no	yes	no	no	no	no	yes	yes
yes	no	yes	yes	yes	no	yes	no	no
yes	yes	yes	yes	yes	yes	yes	no	no
no	no	no	no	no	no	no	no	no
no	no	no	no	no	yes	yes	no	no
yes	no	no	yes	no	yes	yes	no	no
no	no	yes	yes	yes	no	yes	yes	yes
no	yes	yes	yes	yes	no	no	no	yes
no	yes	no	no	no	yes	no	no	no
no	no	yes	yes	yes	no	yes	yes	yes
yes	no	yes	yes	yes	yes	yes	no	yes
yes	yes	no	yes	yes	yes	yes	no	yes
yes	yes	no	yes	yes	yes	yes	no	yes
yes	yes	yes	yes	yes	no	yes	no	yes
no	yes	yes	yes	yes	no	no	yes	yes

Table C-6: Terrabona Themes

Community	Qual	Quant	Cont	Clim	Conf	Org	Fenc	Clean	Forr	Gov	Com.	Roads	Tar	Sav	Mat	ApTec	ExSup
Apatu	no	yes	yes	yes	yes	no	yes	yes	yes	no	no	no	no	no	no	no	yes
Chaguitillo	yes	yes	no	yes	no	no	no	no	no	yes	no	no	no	no	no	no	yes
El Arado	no	yes	no	yes	no	no	yes	no	no	no	no	no	no	no	no	yes	no
El Hatillo	no	yes	no	yes	yes	no	no	no	yes	no	no	no	no	no	no	yes	no
El Balsamo	yes	no	no	no	yes	no	yes	yes	yes	yes	no	no	no	no	no	yes	yes
El Caracol	no	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	no	yes	yes	yes	yes	yes
El Rincon	no	yes	yes	no	no	yes	yes	yes	yes	no	no	no	yes	no	yes	yes	yes
El Rodeo	yes	yes	yes	no	no	no	no	yes	yes	yes	yes	no	no	no	yes	yes	no
La Ceiba	no	yes	yes	no	no	no	no	yes	yes	yes	yes	no	no	no	yes	yes	yes
Monte Grande	yes	yes	yes	yes	no	yes	yes	yes	yes	no	yes	yes	yes	yes	no	yes	yes
Monte Verde	yes	no	no	no	no	no	no	yes	no	no	no	no	no	no	no	no	yes
Ocotillo	no	yes	yes	yes	no	no	yes	no	yes	yes	yes	no	yes	no	no	no	no
Payacuca	yes	yes	yes	yes	no	yes	yes	yes	yes	no	yes	yes	yes	yes	yes	no	yes
Puntisuela	no	yes	yes	no	yes	no	no	no	no	no	no	no	no	no	yes	yes	no
San Juan las Conoas	yes	yes	yes	yes	no	yes	no	yes	no	no	no	yes	no	no	yes	yes	yes
San Pedro	yes	yes	yes	yes	no	yes	yes	yes	yes	no	yes	no	yes	no	yes	no	yes
Santa Rosa	no	yes	no	no	yes	no	yes	yes	yes	yes	yes	yes	no	no	no	no	no

Table C-7: Terrabona Factors

Community	Government	Ext. Supp.	Finances	Manage	Infra	Wat. Res.	Wat. Sys. Funct	Tech.
no	no	yes	no	no	no	yes	no	no
no	yes	yes	no	no	no	no	no	no
no	no	no	no	no	no	no	no	no
no	no	no	no	no	no	no	no	no
no	yes	yes	no	no	no	yes	no	no
yes	yes	yes	yes	yes	no	yes	no	yes
yes	no	yes	yes	no	no	yes	no	yes
no	yes	no	no	yes	no	yes	yes	yes
no	yes	yes	no	yes	no	yes	no	yes
yes	no	yes	yes	yes	yes	yes	yes	no
no	no	yes	no	no	no	yes	no	no
no	yes	no	yes	yes	no	no	no	no
yes	no	yes	yes	yes	yes	yes	no	yes
no	no	no	no	no	no	no	no	yes
yes	no	yes	no	no	yes	yes	yes	yes
yes	no	yes	yes	yes	no	yes	no	yes
no	yes	no	no	yes	yes	yes	no	no

APPENDIX D: GRAPHICAL MODELING AND NETWORK ANALYSIS

This appendix presents supplemental material for the graphical modeling techniques used in Chapter 4. It also presents the R code used to build networks and perform betweenness centrality on stakeholder factor networks (Chapter 3), and to iteratively build graphical models with the Nicaragua case study data (Chapter 4). Sources referenced in this appendix may be found in the Dissertation References section at the end of this thesis.

GRAPHICAL MODELING – SUPPLEMENTAL INFORMATION

Graphical models display interdependencies based on patterns of conditional dependencies. These patterns ultimately emerge through the identification of conditional independencies (or connections between factors that DO NOT exist).

In probability, two variables A and B are said to be independent if:

$\Pr(A \cap B) = \Pr(A) \Pr(B)$

Or if $\Pr(A|B) = \Pr(A)$

Similarly, two random variables X and Y are said to be independent for each value of x and y if:

$f_{X,Y}(x, y) = f_X(x) f_Y(y)$

Or if

$f_{Y|X}(y|x) = f_Y(y)$

For the concept of conditional independence, if we have three random variables, say X, Y, and Z – and if for each value of z, X and Y are independent in the conditional distribution given Z = z, then we say X and Y are conditionally independent of Z, and write (Edwards 2000)

$X \perp Y \mid Z$, or $f_{X|Y,Z}(x|y, z)$

An exemplar extension of this concept of conditional independent may best be made by directly moving forward with an example graphical model. In graph theoretic terms, one could say graphical models are $G = (V, E)$ which is a structure where V is a set of verticies (nodes), and a finite set E of edges, also known as arcs, between these vertices, within the graphical model G. Edges for a graphical model can either be directed, undirected, or bidirected. An example graphic displaying three similarly structured graphs with each edge type is show in Figure D-1**.** Undirected edges indicate a dependency between two variables with no explicit statement on the direction of influence (i.e., A on B or B on A). Conversely, directed edges imply a direction of influence from one variable on another, typically presented as an arrow, where bidirected edges imply either variable can influence the other. In the case where graphs are composed of only undirected edges, the graph is called an *undirected graph*. In the case where a graph has directed edges, it is known as a *directed graph*.

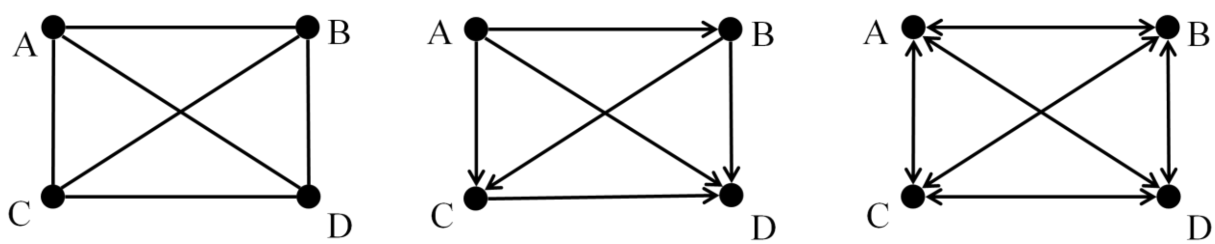

Figure D-1: Example of three edge and graph types: Undirected (left), directed (middle), bidirected (right)

For this study, the extrapolation of data to form directed or bidirected graphs would appear to offer the most advantages in explicitly ascertaining characteristics for both factor influence and structure. However, there are statistical limitations when working with directed graphs that make them less appealing for this study. The majority of work dealing with directed graphs deals with graphs that are acyclic, meaning there can be no formation of loops, a form of graph known as direct acyclic graph (DAG). As such, DAGs are typically implied for most directed graphs, since directed cycles (feedback) may not be modeled as there is no joint probability density function to model this situation (Whittaker

1990). Because we are concerned with exploring the structural interaction between factors, and not necessarily direction of influence, and we do not want to be confined by the statistical limitations of DAGs, we elected to use undirected graphs. For this same reason, undirected graphs are often best used for exploring structure before moving forward with the creation of directed graphs, if this level of detail is needed (Whittaker 1990).

Additionally, an important piece of terminology which will be useful to explain the research methodology is *graph completeness*. A complete graph is one which has an edge between every pair of vertices (Edwards 2000). It can be shown below that each of the graphs shown in Figure D-1, despite the type of edge, would be considered a compete graph. Even if a graph is not complete itself, it may still be broken down into one or more complete sets known as *cliques*. For example, while the figures below are complete graphs $\{A, B, C, D\}$, these graphs may also be broken down into four separate three node cliques, $\{A, B, C\}$, $\{A, B, D\}$, $\{A, D, C\}$ and $\{B, D, C\}$. This could also be done in a similar way for two node cliques.

As mentioned earlier, for a graphical model, dependence between two variables, say A and B, is denoted graphically by creating a line (undirected) or arrow (directed or bidirected) between A and B nodes. Graphical models are built through the identification of conditional independencies between variables that hold for probability densities in the model (Edwards 2000). For example, in figure D-2 below, it can be seen that one edge between nodes is not drawn, namely $C \sim D$. Mathematically, this can be written as $C \perp D \mid A, B$, which states that C is conditionally independent of D given the configuration with A and B, which means there is no line drawn between these two nodes.

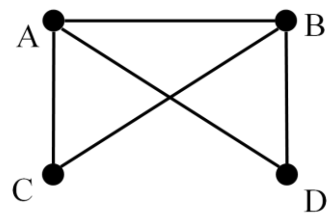

Figure D-2: Example undirected graph

Lines that are drawn denote conditional dependency. Graphs such as this may be interpreted using the global Markov property for undirected graphs, which states (Edwards 2000):

If two sets of variables a and b are separated by the third set of variables C, then $A \perp B \mid C$.

Graphical models can be used to display conditional dependency between discrete or continuous data. Log-linear models are typically used with discrete data, where as continuous data uses models based on multivariate normal distribution analogous to log-linear models, or *Gaussian graphical models* (Edwards 2000). Since the data in this study are discrete (dichotomous) data, we will focus our efforts in explaining the method for using log-linear models.

We will begin the mathematical explanation of log-linear modeling using the undirected graph in Figure D-3 in a way similar to Edwards (2000). In this graph these random variables A, B and C can take on n values or "levels", which we can replace with i, j, k and l as level values for A, B and C. The values for four variables, each having N observations could be appropriately described within a 3 x 3 matrix or table, or a "three-way" table. In this case, the probability that any of N observations might fall within a given cell of that table, is $p_{i,j,k,l}$. Therefore, the simplest model for A, B and C, considering all variables are independent would be:

$$\ln(p_{i,j,k,l}) = u + u_i^A + u_j^B + u_k^C$$

Where the u's are unknown parameters called interaction terms.

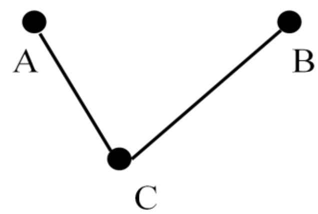

Figure D-3: A simple undirected graph

To model these interaction terms, an ANOVA-like factor expansion is typically conducted with the u's, typically using the unrestricted or "saturated" model (explained later). The saturated model implies that all variables are conditionally dependent (i.e., the whole graph is complete), demonstrated for the model in Figure D-2.

$$\ln(p_{i,j,k,l}) = u + u_i^A + u_j^B + u_k^C + u_{ij}^{AB} + u_{ik}^{AC} + u_{jk}^{BC} + u_{ijk}^{ABC}$$

Where in the case for Figure D-3, $u^{AB} = u^{ABC} = 0$, where the appropriate model would emerge from setting $u_{ij}^{AB} = 0$ for all i and j and similarly $u^{ABC} = 0$ for all i, j and k. This demonstrates what is called a hierarchical log-linear model which means if a term is set to zero, all higher order terms are set to zero as well, where in most cases, hierarchical log-linear models are of interest (Højsgaard 2012). Generally fitting a graphical model to data uses this understanding of hierarchy to simplify model fitting by breaking the model into hierarchical chunks.

For multinomial sampling of N observations, the likelihood function (in the case of a three-way table used for the case of example graph A, B and C) for the table $\{n_{ijk}\}$

$$£(\{p_{ijk}\}|\{n_{ijk}\}) = \frac{N!}{\prod_{ijk} n_{ijk}} \prod_{ijk} p_{ijk}^{n_{ijk}}$$

Therefore, the maximum likelihood estimates that maximizes this expression are:

$$l(\{p_{ijk}\}|\{n_{ijk}\}) = \ln\left(\frac{N!}{\prod_{ijk} n_{ijk}}\right) + \sum_{ijk} n_{ijk} \ln(p_{jkl})$$

A similar formulation of this maximum likelihood equation, albeit more complicated, could be done for larger data sets, and is facilitated in this research using R-Project. The MLE is the statistical basis for model selection, described in the next section.

MODEL SELECTION

One of the main difficulties with using graphical modeling to fit a particular multivariate data set, is that there are generally a myriad of different well-fitting model structures (Whittaker 1990). This is because, in the case of even a 15 node undirected graph, the number of undirected possible graphs is $2^{15x14/2} = 4.05 \times 10^{31}$. Because of this, the likelihood of having the true optimally best-fit model is not good. However, in the case of this research, an optimal fit is less desirable than a good fitting model that helps us gain insight into the implication of model structure. There are generally three types of model fitting algorithms, (Højsgaard 2012):

1. Use of low-order conditional independence tests to infer structure of the joint model;
2. Heuristic search to optimize some criterion;
3. Bayesian methods, often involving Markov chain Monte Carlo Methods.

In the case of this research which is focused on a high-level, exploratory development of model structure, we opted to use the first method, where further exploration and refinement of the model could take place in future studies if so desired (Højsgaard 2012). The first method, also known as a *step-wise* method, selects the model that best fits a particular criterion, also known as a penalized likelihood. This is accomplished by iterating through model structures (including or excluding edges between nodes), where inclusion or exclusion of edges is decided using significance tests. Edwards (2000) suggests at each step using a chi-squared tests based on the difference between subsequent models in which the edge whose chi-squared test has the largest (non-significant) p-value is removed. If all p-values are significant (i.e., all $p < \alpha$) then the process stops (Whittaker 1990, Edwards 2000). This can either be done by *backward* or *forward* selection. Backward selection starts with the saturated (complete) model, and begins deleting edges to fit the model, while forward selection starts from the independent model and adds edges. Typically, backward selection is the preferred selection method since the complete model is generally consistent with the data (Edwards 2000). Another slightly more sophisticated selection criterion may be based on maximum likelihood. As described by Højsgaard (2012), methods of this type consider a set of models Ɛ(j) for $j = 0, 1, \ldots, R$, where the best model is selected back on the Ɛ(j) that minimizes -2log$L(j) + kp(j)$, where L is the maximum likelihood under the model and $p(j)$ is the number of free parameters in the model Ɛ(j) and k is a penalty parameter. Two popular values for k are 2 (Alkines Information Criterion (AIC) (Akaine 1974) and the Bayesian Information Criterion (BIC) (Schwarz 1978) which sets k = log(N). The BIC penalizes models that are more complex, therefore generally giving simpler models. With the stepwise method, the eligible edges are tested for removal (backward selection) or addition (forward selection using the AIC or BIC criteria), deleting or adding the edge that would give the largest decrease in AIC.

Finally, it is worth noting that since model estimation assumes independent realizations of Poisson distribution, it is also possible to use generalized linear models (GLM) in place of log-linear model estimation. However, GLM is typically not recommended for the creation of graphical models if the data sample size is small compared to the relative complexity of the model (Højsgaard 2012). Therefore, given the complexity of the problem we are modeling, and the small level of samples, we opted to use log-linear modeling to fit the data.

NETWORK ANALYSIS – R CODE

Presented below is the network analysis code used to perform betweenness centrality (point and graph) on the stakeholder value networks (Chapter 3) using community Water Committee stakeholder opinion. Similar code was used to perform these same analyses for the other three stakeholder groups.

```
#Network Analysis Packages
library(igraph)
library (statnet)
library(network)
library(sna)

#######################################
#Network Analysis: Community Stakeholders
#######################################

#Communty Betweenness Calculations
#build a blank adjacency matrix
fcom = matrix(0, nrow = 9, ncol = 9 ) # tech, man, community, g&p, WR, Ext, Fin, Com, T&E (9)
fcom <-network(fcom,directed=FALSE)
fcom = as.sociomatrix(fcom)
namescom = c('WSF','Tech', 'Man','G&P','WR','Fin','Com1','T&E', 'Ext') # individually
rownames(fcom, do.NULL = TRUE, prefix = "row")
rownames(fcom) <- namescom
colnames(fcom, do.NULL = TRUE, prefix = "col")
colnames(fcom) <- namescom
fcom # blank socio matrix with names

# filling the adjacency matrix directly based on interactions indicated in focus groups
fcom[1,6]<-1
fcom[2,1]<-1
fcom[2,5]<-1
fcom[2,8]<-1
fcom[3,1]<-1
fcom[3,7]<-1
fcom[3,8]<-1
fcom[3,9]<-1
fcom[4,1]<-1
fcom[4,3]<-1
fcom[4,7]<-1
fcom[4,8]<-1
fcom[4,9]<-1
fcom[5,1]<-1
fcom[5,2]<-1
fcom[6,1]<-1
fcom[6,3]<-1
fcom[6,8]<-1
```

```
fcom[6,4]<-1
fcom[6,2]<-1
fcom[6,7]<-1
fcom[6,9]<-1
fcom[7,1]<-1
fcom[7,8]<-1
fcom[7,9]<-1
fcom[8,1]<-1
fcom[8,4]<-1
fcom[8,5]<-1
fcom[8,3]<-1
fcom[8,2]<-1
fcom[8,6]<-1
fcom[8,9]<-1
fcom[9,1]<-1
fcom
betcom <-betweenness(fcom, gmode = 'digraph') #betweenness calc
betcomnorm<-betcom/((NROW(fcom)-1)*(NROW(fcom)-2))
betcomnorm
gplot(fcom,label=colnames(fcom[,]))

#Performed the centralization calc  for community water committee stakeholder group
Centcom = matrix(,nrow = NROW(betcom),ncol = 1)
for(i in 1:NROW(betcom)){
  Centcom[i] = max(betcom) - betcom[i]
}
#normalizing the centralization score based on the maximum score available (star or wheel)
Centcomnorm = sum(Centcom)/(NROW(betcom)^3 + -4*NROW(betcom)^2 + 5*NROW(betcom) -2)
Centcomnorm # outputs the normalized betweenness
```

GRAPHICAL MODELING – R CODE

The code presented below was used to build probabilistic graphical models of the factors that influence rural water infrastructure sustainability in Darío and Terrabona (code only shown for Terrabona). These model graphs were later structurally analyzed using network analysis, using the same code shown above for point and graph betweenness scoring using the resulting adjacency matrix.

```
#Graphical Modeling packages
library(RBGL)
```

```
library(gRain)
library(gRim)
library(Rgraphviz)

########################################
#Terrabona Graphical Model
########################################

#load binary factor data from computer
DatafactorsTerra = read.csv("C:/Users/Jeff/Dropbox/PhD/R/Terrabona_Matrix_1.csv") #Factors

#performs the step model selection
testStepFactorsTerra <- dmod( ~.^., data=DatafactorsTerra)
modelFactorsTerraAIC <- stepwise(testStepFactorsTerra, details=1, k=2) #AIC since K = 2
ugFactorsTerraAIC <-ugList(terms(modelFactorsTerraAIC),result  = 'igraph') #puts into graphable format

plot(ugFactorsTerraAIC);

#adjacency matrix output for network analysis
FactorsTerraadjAIC <- ugList(terms(modelFactorsTerraAIC), result="matrix") # pulls out adjacency matrix

#put them into network format for subsequent structural analysis using betweenness centrality
FactorsNetworkAICTerra <-network(FactorsTerraadjAIC,directed=FALSE)
FactorsNetworkAICTerra <- as.sociomatrix(FactorsNetworkAICTerra)
```

APPENDIX E: IRB APPROVALS

This section presents the Institutional Review Board (IRB) Approvals for the Delphi and Cross Impact study, as well the Nicaragua case study.

APPROVAL FOR DELPHI AND CROSS IMPACT STUDY

University of Colorado Boulder

Institutional Review Board
563 UCB
Boulder, CO 80309
Phone: 303.735.3702
Fax: 303.735.5185
FWA: 00003492

30-Jan-2014

Exempt Certification

Walters, Jeffrey
Protocol #: 13-0705
Title: Qualitative System Dynamic Modeling of Causal Factors for Sustainable Rural Water Services in Developing Countries

Dear Jeffrey Walters,

The Institutional Review Board (IRB) has reviewed this protocol and determined it to be of exempt status in accordance with Federal Regulations 45 CFR 46.101(b). Principal Investigators are responsible for informing the IRB of any changes or unexpected events regarding the project that could impact the exemption status. Upon completion of the study, you must submit a Final Review via eRA. It is your responsibility to notify the IRB **prior** to implementing any changes.

Certification Date: 30-Jan-2014
Exempt Category: 2

Click here to find the IRB reviewed documents for this protocol: Study Documents

The IRB has reviewed this protocol in accordance with federal regulations, university policies and ethical standards for the protection of human subjects. In accordance with federal regulation at 45 CFR 46.112, research that has been approved by the IRB may be subject to further appropriate review and approval or disapproval by officials of the institution. The investigator is responsible for knowing and complying with all applicable research regulations and policies including, but not limited to, Environmental Health and Safety, Scientific Advisory and Review Committee, Clinical and Translational Research Center, and Wardenburg Health Center and Pharmacy policies.

Please contact the IRB office at 303-735-3702 if you have any questions about this letter or about IRB procedures.

Douglas Grafel
IRB Admin Review Coordinator
Institutional Review Board

APPROVAL FOR NICARAGUA CASE STUDY

University of Colorado Boulder

Institutional Review Board
563 UCB
Boulder, CO 80309
Phone: 303.735.3702
Fax: 303.735.5185
FWA: 00003492

APPROVAL

16-May-2014

Dear Jeffrey Walters,

On **16-May-2014** the IRB reviewed the following protocol:

Type of Submission:	Amendment
Review Category:	Exempt
Title:	Qualitative System Dynamic Modeling of Causal Factors for Sustainable Rural Water Services in Developing Countries
Investigator:	Walters, Jeffrey
Protocol #:	13-0705
Funding:	Non-Federal
Documents Approved:	Question Summary; Informed Consent Declaration (16May14); Recruitment Materials; 13-0705 Protocol (15May14);
Documents Reviewed:	Collection of Observations & Documents; HRP-213; Protocol Amendment; Local review letter related to Jeff Walter�s resea; ForeignLocalReviewLetter;
Description:	Update to study for data collection in Nicaragua.

The IRB approved the protocol on **16-May-2014**.

Click the link to find the approved documents for this protocol: Approved Documents. Use copies of these documents to conduct your research.

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

Sincerely,
Douglas Grafel
IRB Admin Review Coordinator
Institutional Review Board

APPENDIX F: SYSTEMS-BASED SUSTAINABILITY ANALYSIS (SSA) FRAMEWORK

INTRODUCTION

This appendix presents the framework proposed in Chapter 5 as a practical contribution of this research for the water sector. The intention of this framework is to aid water practitioners and researchers with the decision making process for strategic planning and management of rural water infrastructure in developing countries through a systems-based analysis of factors that influence project success. It is to be noted, however, that this framework is still in pilot form. Therefore, the reader must take care in using this framework, as its true efficacy has not yet been tested in a stand-alone form. Despite this fact, it is the hope of the author that this framework can demonstrate a practical integration of the methods used in this dissertation to aid in the pursuit of sustainable rural water infrastructure in developing countries.

The ideal domain (boundary) for use of this framework would be set at the regional or municipal level (i.e., multiple communities), where the corresponding strategic planning of rural water infrastructure will take place. Specifically, this framework guides practitioners, researchers, and key-project stakeholders through the process of identifying factors that influence success of projects within a particular region by iteratively modeling the systemic interaction of these factors through group and empirical model building and analysis. The goal of these modeling efforts is to provide an improved understanding of the important or impactful factors that influence rural water infrastructure, based on a systemic understanding on how these factors interact. As with Appendix D, all sources referenced in this appendix are presented in the Dissertation References section, immediately following this framework.

OVERVIEW OF THE FRAMEWORK

Structural analysis is a means to link up ideas to better understand the *root causes* of a particular issue (Arcade et al. 2001). The proposed framework herein, called the “Systems-based Sustainability Assessment (SSA) Framework”, follows either a 5-step or 10-step model building process that ends with a decision for strategic action – whether that be implementation of a rural water project or direct changes in management or policy, etc. – based on the insight gained through the systems-based structural analysis of factor interaction diagrams and networks. The initial (and requisite) 5-step process is called “Structured Group Model Building and Analysis” (SGMB), a participatory method which takes place in model building workshops where participants build informative models during multiple workshop sessions. If decision makers require further information to make a decision for programmatic action, the second 5-step process called “Empirical Model Building and Analysis” (EMB), offers additional context-specific insight into the realities in the field by comparing factor structures derived from computational modeling with factor structures from the previous SGMB sessions. An overview of the entire modeling framework is shown in Figure F-1, and is explained in the sections that follow.

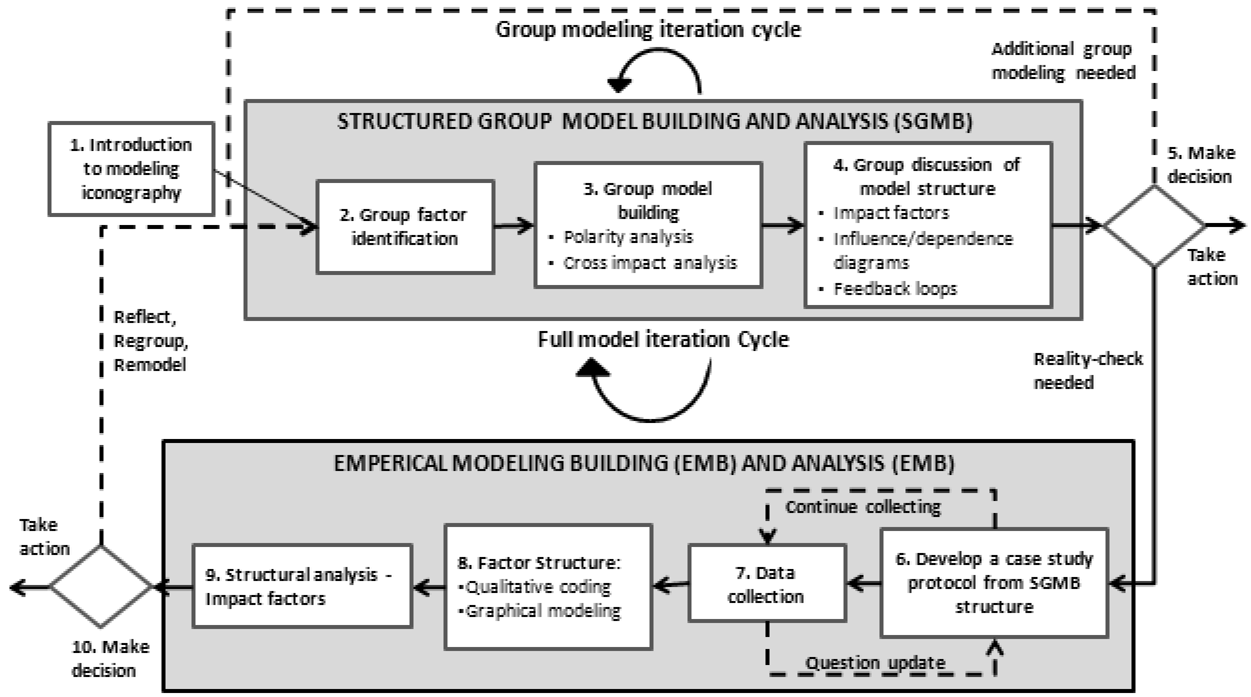

Figure F-1: An overview of the Systems-Based Sustainability Analysis (SSA) Framework

STRUCTURED GROUP MODEL BUILDING AND ANALYSIS (SGMB)

Arguably the most important outcome of any modeling process is the increased insight and deeper understanding that may result merely from engaging the act of modeling itself (Pruyt 2012; Godet 1986; Richmond 2001; Saeed 2001). Thus, the proposed framework engages key project stakeholders and practitioners throughout the entire factor modeling process. This process begins with SGMB (Steps 1 through 5, Figure F-2). The core concept of SGMB finds it roots in a popular application of system dynamics modeling known as Group Model Building (GMB). GMB is a method specifically targeted at engaging stakeholders in the process of building models to improve decision making in the face of complexity (Richardson 1995; Vennix 1996; Hovmand 2012). Vennix (1996) describes GMB as "a process in which team members [i.e., practitioners, stakeholders, experts, etc.] exchange their perceptions of a problem and explore such questions as: what exactly is the problem we face? How did the problematic situation originate? What might be underlying causes? AND most importantly "How can the problem be effectively tackled? (p.3)." The overarching goal of GMB is to take participants' mental models that exist as individual implicit frameworks (Vennix 1996), and make these frameworks explicit through diagramming and quantitative simulation.

Qualitative system dynamics modeling (diagramming) is often most appropriate when model variables cannot be accurately quantified, as is often the case for exploratory modeling, similar to what was done in this research. As such, the main benefits of group mode building are the ways that the GMB process enables workshop participants to (i) formalize and align their mental models within a group to learn how certain factors cause a complex behavior (Vennix 1996; Andersen et al. 1997; Bérard et al. 2010; Wolstenholm 1982; Cavaleri and Sterman 1997), and (ii) provide a platform with which to discuss a complex problems using a unified method that better facilitates group consensus on possible strategies and future actions (Richardson 1995; Rouwette et al. 2011; Rouwette 2012; Vennix 1997; Visser 2007; Vennix 1993).

Although GMB literature is rich with recommendations on how to best facilitate a GMB workshop, no formal method exists (Vennix 1996; Andersen et al. 1997; Luna-Reyes 2006). However, provided below is an abbreviated example GMB workshop agenda based on these recommendations, in the following 5-steps (Vennix 1996):

Step 1: Introduce workshops participants to diagramming iconography
Step 2: Brainstorm problem variables
Step 3: Identify variable interaction and polarity
Step 4: Identify feedback loops to promote conversation on model implications
Step 5: Debrief overall model outcomes and potential strategic action(s)

Similar to these 5 steps above, the 5-step structured group model building and analysis (SGMB) process exploits the benefits of GMB, while offering a different approach to model building by adding a more “structured” approach to traditional GMB. Specifically, this structure enters into Steps 3 and 4 above, through the use of *cross impact analysis* (CIA) and *polarity analysis*. However, the end goal of SGMB is the same as GMB: to facilitate group consensus on thoughtful strategies and future actions for rural water project implementation and policy. The time duration needed to perform a SGMB in whole, is two to three eight-hour days.

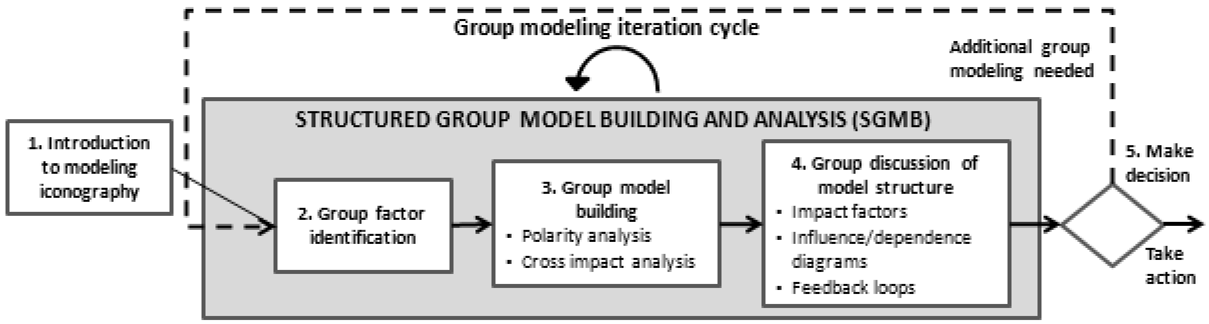

Figure F-2: The SGMB process

<u>Step 1: Introduction to model building iconography:</u>

As is the case in traditional GMB, the goal of the SGMB exercise typically culminates in the development of a model from which important insights can inform some sort of *strategic action* (Andersen et al. 1997). These important insights are fostered through the identification of *impact factors* and *feedback mechanisms*. Impact factors are variables that have the greatest influence on other factors, and thus on the model outcome. The model outcome in this case is the long-term success of a rural water system. Feedback mechanisms are loops of circular causality between factors hypothesized to drive the dynamic behavior of the model (Forrester 1961; Sterman 2000; Richardson 2011).

The first SGMB workshop begins with brief description of diagramming iconography based on *qualitative system dynamic modeling* (factors, arrows, and polarity), and of the overarching workshop goals (finding impact factors and feedback loops) to workshop participants. Factors are described as the elements needed to represent the problem being modeled. Arrows are described as indicating the influence between factors, where the direction of the arrow indicates the direction of influence (i.e., Factor A → Factor B means Factor A influences Factor B). Polarity indicates the type of influence is taking place between factors, where a positive polarity (+). Feedback mechanisms that emerge during and after the modeling process – which imply circular causality exits between model factors – may be discussed in this step, or saved until the first conceptual model is built. The basic modeling iconography that can be shown in the workshop is shown in Figure F-3.

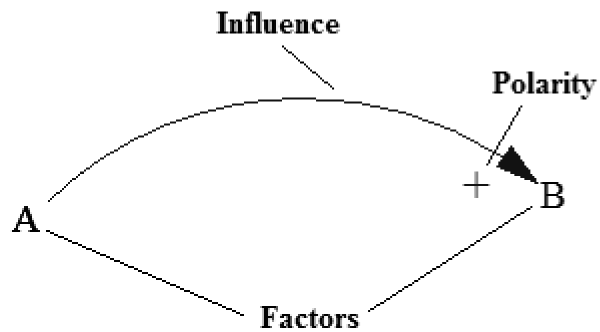

Figure F-3: Typical qualitative system dynamics diagramming iconography

Step 2: Group Factor Identification:

The first critical step in model building is to describe the problem that is to be modeled (Richmond 2001). While the problem may be obvious, (i.e., lack of sustainability of rural water infrastructure), this problem may be a result of drastically different factors or "causes" in a different regional context (Ramalingham 2008). That said, once the problem has been clearly identified, the next major step is then to describe the "boundary" of the problem; that is, the spatial "box" within which the causes of the problem are encapsulated (Sterman 2000). All factors within this box are then assumed to interact "endogenously", meaning the emergent outcome of the model is a result of the internal structural interaction of factors. The process of identifying factors is then accomplished through brainstorming, a proven way to foster the outpouring of ideas (Vennix 1996), a process which can take as little as an hour or as long as a whole day. Often the best way to brainstorm with group model building is to use a whiteboard to write down all the ideas (factors), and to then aggregate factors into affiliation groups (Walters and Litchfield 2015). The end goal of factor aggregation is to create a model that is easier to grasp, while making the subsequent polarity analysis and cross impact analysis phases of this framework (Step 4) easier to conduct. Regardless of the number of factors and the extent of factor aggregation, the group must reach consensus on the definition and meaning of each factor before moving on to the next step.

Step 3: Group Model Building:

The group model building process entails taking the factors and drawing meaningful connections between them. These connections are meaningful because they imply influence, or even causality; although causality, in terms of "causing" something else to happen, is often a tenuous claim (Bennear 2014). While there are numerous forms this diagramming process can take, the SSA framework specifically focuses on two forms from which emerge two distinct outcomes. The first form is polarity analysis (for more information on polarity analysis see Chapter 2 of this dissertation), which involves systematically identifying the influence and polarity between each factor. The emergent outcomes from a polarity analyses are feedback loops which may be characterized based on the polarities within the loops. The identification and characterization of feedback loops will be discussed in the next section. The second form of analysis is called a *cross impact analysis*, which entails adding strengths to influences as a way to later indicate factor importance and dynamic influence. Both of these analyses should begin as diagrams drawn on the whiteboard or chalkboard, however; it is the author's recommendation to take the time necessary to electronically re-draw the diagrams in order to clearly show all influences to modeling participants. These two showcased analysis forms are described below.

Polarity Analysis: The polarity analysis diagramming process entails focusing on each individual factor and considering its respective influence on every other factor. If an important connection exists, as determined by the group, an arrow and its associated polarity (+ or -) is drawn between the factors. If a connection does not exist, an arrow is not drawn. Figure F-4 displays an example in which Factor A was determined to have a positive polarity on Factor B, a negative polarity on Factors D and E, and no influence on Factor C. In this example, the process would then be repeated for Factors B, C, D and E until all potential influences were considered. This diagramming process usually takes between 1 - 3 hours, depending on the number of factors included in the model. One can quickly see the merit of this process with smaller number of factors (n), as the number of individual influences the group must consider is $n^2 - n$. The final outcome from the polarity analysis is a complete causal loop diagram (CLD) displaying the systemic influence between factors.

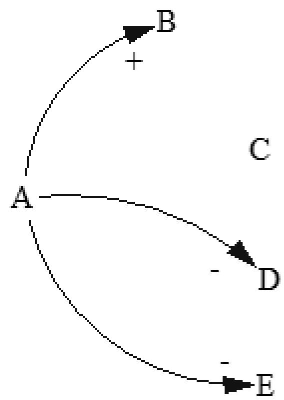

Figure F-4: A visual example of the diagramming process, starting with Factor A (Walters and Litchfield 2015)

Cross Impact Analysis: The cross impact analysis diagramming process follows a similar initial process as polarity analysis. Cross impact analysis involves assigning an influence or "strength" to each of the influences found to exist between factors. Since the polarity analysis is typically done first, the influences will have already been drawn. Thus, all that is required is to revisit the influence diagrams and, for each "arrow", indicate influence strength. Influence strength is typically categorized with a score of: 0 – no influence, 1 – weak influence, 2 – moderate influence and 3 – strong influence (Godet 1986). The result from this analysis is an *impact matrix* that displays the influence of factors on the other factors. If a computer and projector are available, the process of indicating influence strengths may be streamlined by simultaneously entering strengths into an impact matrix within a CIA software, such as Lipsor's MICMAC (http://en.laprospective.fr/, Figure F-5), which automatically displays influence strengths in different colors on an *influence graph* (Figure F-6). If a computer and projector are not available, a possible solution is to trace over the influences with a colored marker, using consistent coloring for each influence strength. The end goal of this exercise is to develop a diagram which shows the relative strengths of influence between factors and illuminates impact factors, factor influence, and dominant loops, described in the next section.

Matrix of Direct Influences (MDI)

.	1 : G&P	2 : Tech	3 : Infra	4 : Comm	5 : Fin	6 : Ext	7 : WR	8 : WSF
1 : G&P	0	3	3	3	3	0	1	0
2 : Tech	1	0	0	3	3	0	3	3
3 : Infra	3	3	0	3	3	3	2	3
4 : Com	1	1	0	0	3	2	3	3
5 : Fin	3	3	0	3	0	0	3	0
6 : Ext	3	3	0	3	0	0	3	0
7 : WR	3	0	0	0	3	0	0	3
8 : WSF	3	1	0	3	3	0	3	0

Figure F-5: Example Lipsor MICMAC impact matrix

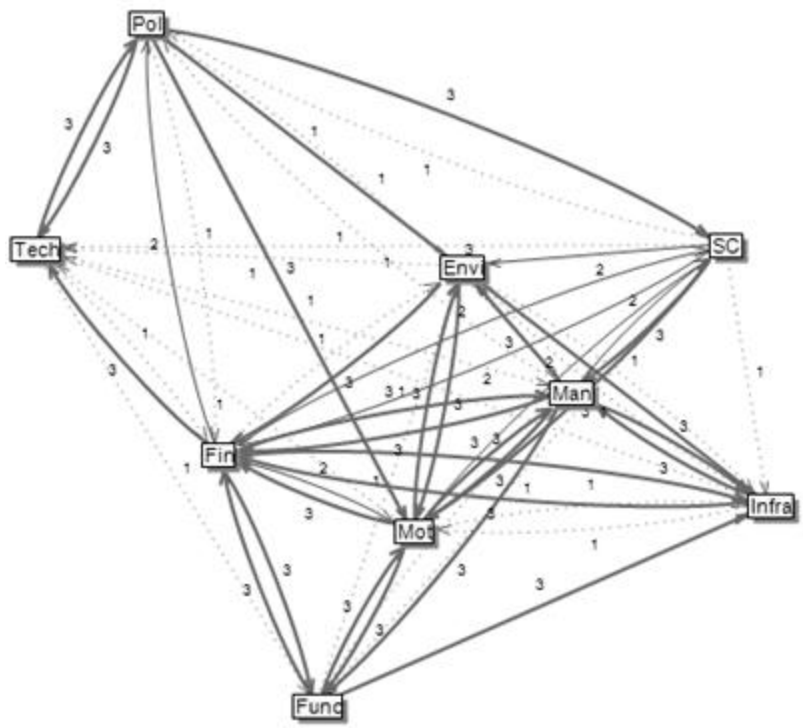

Figure F-6: Example influence graph in Lipsor's MICMAC (**bolder** lines = stronger influences)

Step 4: Discussion of Model Structure

Once the group has a diagram showing factor influence and strength, the next step is to use these diagrams to gain insight into factor importance (impact factors), and to infer factor dynamics (feedback mechanisms). With CLDs, influence graph, and impact matrices, it is possible to do four types of structural analysis, each providing a unique form of insight into factor and loop importance. These four types of structural analysis are: *feedback loop identification and characterization*; *loop dominance based on cross impact data*; *influence mapping based on cross impact data*; and *network analysis* in the form of factor centrality and network scoring.

Feedback Loop Identification and Characterization: A feedback loop exists when a circular causality exists between two or more factors (Richardson 1999). In other words, the chain of influence begins and re-influences the beginning factor in succession over time. Feedback loops can be used to hypothesize the drivers of dynamic or emergent behavior. An example CLD which describes the feedback mechanisms that drive a particular dynamic behavior could be: an increase in population causes an increase in people being born, which causes an increase in population, and so on (see Figure F-7).

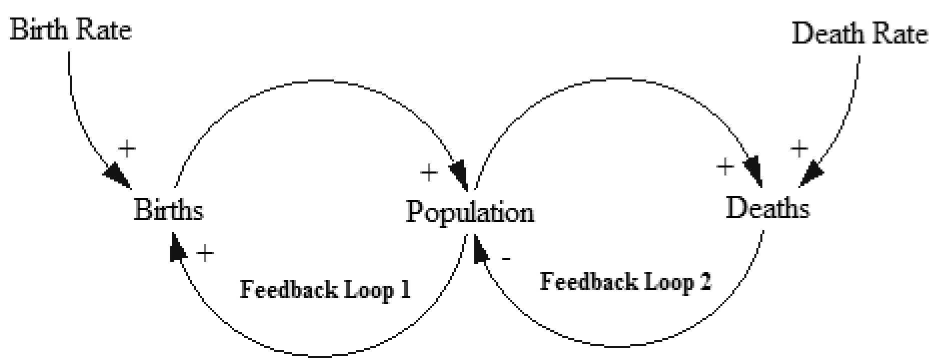

Figure F-7: Example CLD for population dynamics (Walters and Litchfield 2015)

There are two types of feedback mechanisms: reinforcing, and balancing. Reinforcing loops cause an exponential increase or decrease in behavior (an increase or decrease in water system functionality, for example), and are generally unstable over time. Using Figure F-7 as an example, the reinforcing feedback loop 1, could be the exponential increase in population over time. Conversely, a balancing loop causes a type of stability, or regulating constraint, and ultimately a goal seeking type of behavior. Again, using Figure F-7 as an example, the exponential increase in population is stabilized by the number of people dying (balancing feedback loop 2), where the overall population would reach a stable equilibrium over time.

Identifying feedback loops with a CLD can be a simple process if modeling programs (such as Ventana Systems Inc.'s VENSIM) are used to systematically identify loops, using the "loop" identification tool. Once loops are identified, it is possible to discern the nature of dynamic influence by summing up the number of negative influences (Sterman 2000). If the sum of negative influence polarities is an odd number, the feedback mechanism is balancing, whereas if the sum is positive, the feedback mechanism is reinforcing (Richardson 1984). In this way, all feedback mechanisms may be identified and characterized, and the emergent behavior may then be inferred and discussed within the group to gain insight into potential causes of problematic behavior.

Loop Dominance: Once each feedback mechanism is identified and characterized, the next step is to understand which loop is most influential or "dominant". This may be accomplished by a simple process of summing up the individual influence strengths found through the CIA, and normalizing this sum by the number of influences in the loop (per Chapter 2 of this dissertation). The dominant loop is the one which has the highest overall score, where the highest score would be 3, based on the scoring scheme of 0-3 showcased above. Loop dominance aids in prioritizing the allocation of resources or the systematic roll-out of a particular policy to mitigate a particular issue (such as water consumption, source pollution, or conflicts with household tariff payment).

Influence maps: Summing up the rows and columns of the previously constructed impact matrix allows for the identification of factor influence and dependence. Factor influence is how a factor causes a change in other factors to which it is connected, and factor dependence is how other factors influence a particular factor. Summing the individual columns of the impact matrix demonstrates the dependence of a particular factor on other factors, while row sums demonstrates each factor's influence on the other factors, a process that is illustrated in Figure F-8. The relative influence and dependence of factors on other factors provides a means to understand key aspects regarding the system's evolution (dynamics) towards an end state (Arcade et al. 2001), explained later.

Sum(Row) = Influence

Factor	A	B	C	D
A	--------	1	2	1
B	1	--------	3	0
C	2	1	--------	1
D	2	3	3	--------

Sum(Col) = Dependence

Figure F-8: The matrix mathematics used to identify factor influence and dependence

Influence and dependence may be spatially displayed in a four-quadrant influence/dependence chart called *influence maps*, shown in Figure F-9 (Arcade et al. 2001). The spatial location of a particular factor on the influence maps allows the inference of dynamic behavior based on the spatial location of factors within the four quadrants of the influence map (Shown in Figure F-10). Factors within the *NW Quadrant (Quadrant 1)* are called *influent variables* that strongly condition the system behavior but are not controlled by it (Arcade et al. 2001). Factors that are influent variables (having both high influence and low dependence) can also be thought of as impact factors, in that any effect on said factor would have the highest affect on other factors, and other factors would have very little influence on the factor that was adjusted (i.e., it is robust, resilient, durable, etc.). Factors within the *NE Quadrant (Quadrant 2)* are called *relay variables*, and are highly dependent on other factors and unstable (Arcade et al. 2001). They can be considered, to some extent, a result of the system's evolution over time, as impacted by the *influent variables* (Arcade et al. 2001). Factors within the *SW Quadrant (Quadrant 3)* are known as *autonomous variables*. Autonomous variables have very little influence or dependence from or on other factors (Arcade et al. 2001). Factors in the *SE Quadrant (Quadrant 4)* are known as *depending variables* or *result variables*, and have very low influence and their dependence is highly sensitive to the evolution of influent and relay variables. By assessing factor influence and dependence in this way, it is possible to make strategic decisions about which factors to address through the use of organizational resources. A summary of these distinctions are shown in Figure F-10.

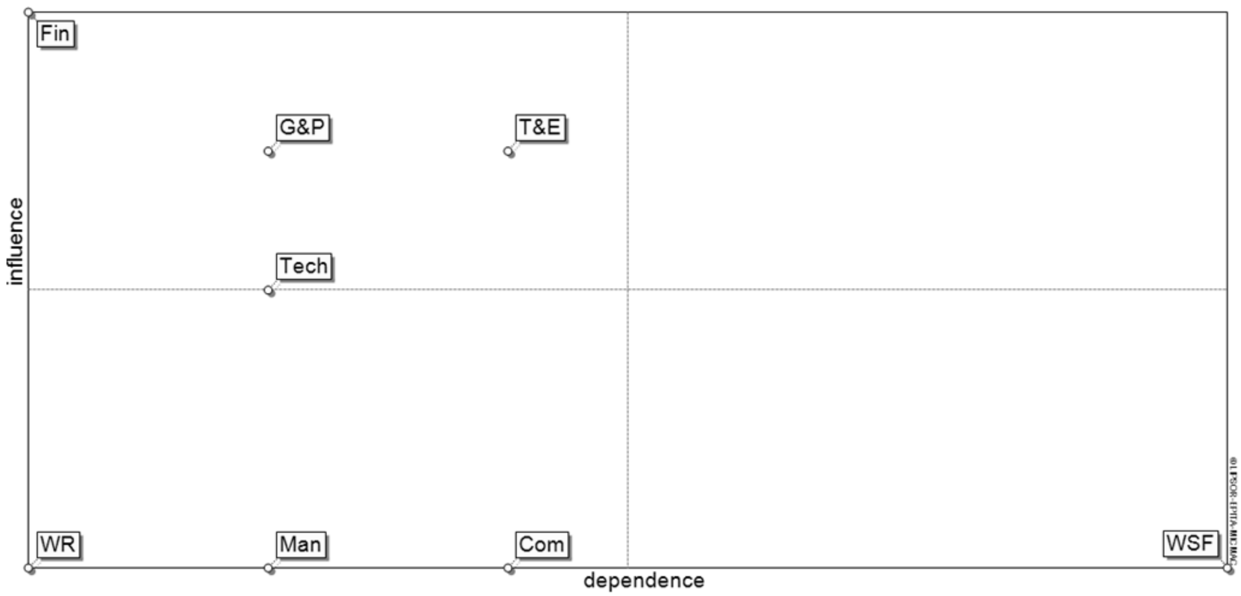

Figure F-9: Example influence map in Lipsor's MICMAC

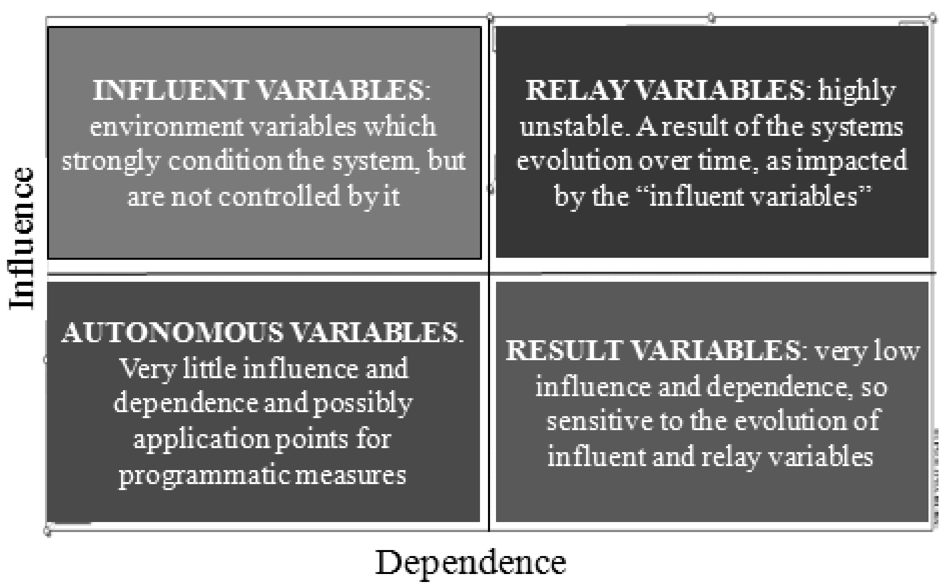

Figure F-10: Summary of influence map quadrant significance

Centrality: Boiled down to their essential components, CLD and cross impact influence graphs are network diagrams composed of nodes (factors), and edges (lines or arrows). Thus, it is possible to structurally identify factor interaction and impact using conventional network analysis methods. Centrality measures are a popular form of network analysis used to identify the "importance" of factors based on various forms of connectedness that may exist between factors. Traditionally, centrality measures take the form of *degree* (direct factor influence on other factors), *closeness* (measured by spatial relationship of a factor with respect to other factors), *betweenness* (measured by the way in which factors serve to bridge the shortest paths to other factors), or *eigenvector* (based the relative importance of other factors that are directly connected to a particular factor) centrality. The decision to use any one of these four centrality measures is for the modeling team; however, the author recommends using betweenness centrality (Walters and Javernick-Will 2015B). For more information on centrality measures, the reader is referred to Scott 2000, and Wasserman and Fraust (1994).

Step 5: Make a Decision

With the structures drawn and analyses performed, the final step is to make one of three decisions, either one of strategic action, further group modeling, or empirical data collection.

Strategic Action: Thoughtful strategic action will be based on the systems-based insight gained through the structural analyses. In general, this will be based on the identification of impact factors and dominant feedback mechanisms. Impact factors will be the factors that emerge as most important through both the influence graphing and centrality analyses. For example, if the most impactful factor is "water resources", such that the most important aspect that must be secured is the availability and source protection of water, then resources must first be placed there. A list of priorities may also be made based on the ranked importance of factors.

Based on feedback loops, the group could take strategic action in the form of a particular plan or policy where various issues that may result from a potentially "destructive feedback mechanism" are temporally addressed in succession. In other words, this process entails choosing to address feedback mechanisms that are reinforcing and potentially destructive with a policy or plan that acts as a balancing feedback loop. This type of approach was been used by Hjorth and Baghari (2006) to make policy decisions for proper water resource management, where they call these types of mitigating balancing loops “viability loops”.

Further Group Model Building: If the group finds contention between factor identification, or is unable to reach consensus on many of the factors, their relative interaction, and the findings inferred by their interaction, it may be necessary to begin the SGMB process again from the start. It will then be important to focusing specifically on reaching complete consensus on factors and their interactions, and working to deal with issues that inhibited reaching consensus. Redoing the model process, however, does have intrinsic advantages associated with the additional confidence gained by comparing the two group models (the previous model with the second model) as a way to judge consistency. Thus, the process of model iteration, should not be considered a step backwards, but instead should be encouraged and executed in earnest if deemed necessary.

Field Data Collection: Despite having a model that provides interesting insight into factor interaction, the group may decide that the results of the model require further validation or comparison with the realities in the field. If this takes place, the next 6 to 10 steps in the SSA framework provide for the collection of data in the field to build factor structures that may be compared to the structures identified through SGMB.

EMPIRICAL MODEL BUILDING (EMB)

When the findings from SGMB do not provide sufficient clarity for strategic action, the next step is to perform a case study within the process of empirical model building (EMB) to highlight some of the realities in the field needed to affirm and confirm the factor analyses that took place in the SGMB. While this process will actively involve fewer stakeholders than SGMB, it is important that the whole group model building team remain in contact throughout the EMB process, and continue to hone in, reflect on, and amend their models build through SGMB in an iterative fashion. The output from these efforts is a similar factor diagram to what was build using SGMB, but instead is a diagram (network) inferred using field data. An overview of the EMB process is shown in Figure F-11.

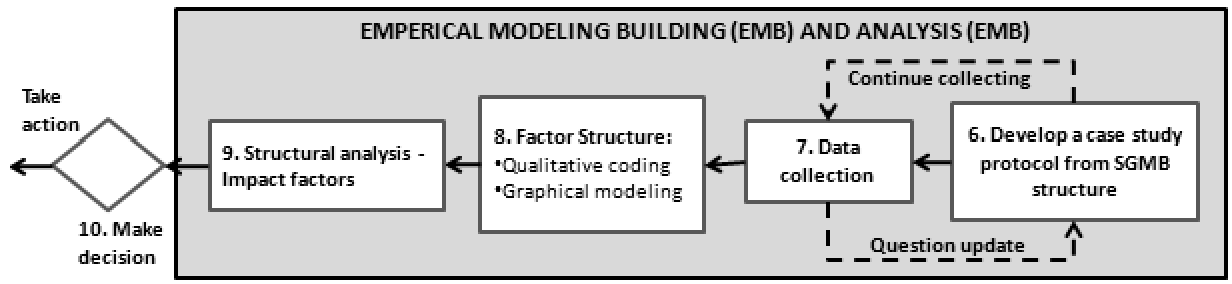

Figure F-11: The EMB process

Step 6: Develop a Case Study Protocol

A case study is an appropriate method for the practitioner who is interested in *exploring* in-depth detail related to a particular "case" within a particular context (Yin 2002). As such, the case study method is the choice way for practitioners to gain additional information to inform the findings from the SGMB.

Similar to the importance of first identifying a cogent description of the problem being modeled within the SGMB process, developing a rigorously constructed *case study protocol* is the cornerstone of a reliable case study. A case study protocol is essentially a "road map" that the researcher will use to guide the case study. Generally, the protocol lays out the introduction and purpose of the protocol, the research questions, the data collection procedures, how the data will be analyzed and evaluated, all the while developing ways for the research to stay focused on identifying patters in the data to effectively answer the predetermined research questions (Yin 2002). While the research questions for each case study on rural water infrastructure sustainability will be unique within the context applied, some generic questions to guide the research protocol may be:

- What are the factors that influence long-term rural water service sustainability
- How do these factors interact?
- How do these factors vary over time?
- Which factors are the most influential?

An important aspect the researcher must consider is how the results of the study (the patterns seen, the theories proposed) can be validated against rival theories. The types of validation that are considered are *construct validity* (do the data that were measured reflect the concepts that were discussed?), *internal validity* (do the conclusions hold up given the evidence within the study?), *external validity* (can these conclusions be generalized amidst other cases?), and *reliability* (what were the biases that existed, did they potentially adversely affect the meaning of the data?). To minimize the potential for rival theories to invalidate the research findings, the practitioner is encouraged to focus heavily on ensuring that the data support tight conclusions and propositions.

The defining aspect for the creation of an effective protocol is the identification of a conceptual (or theoretical) framework that guides the selection of data collection (Miles and Huberman 1994; Maxwell 2004). For the most part, it may be assumed that data collected will be in the form of interviews and surveys, along with field observations and water quality and quantity tests (for detailed information on water quality and quantity tests, see Howard 2002). The process of developing a conceptual framework may be facilitated by referencing recurring themes in model structure from the SGMB workshop, where question design may be based on the desire to understand how factors influence rural water system functionality. However, because factor connections will later be ascertained using probabilistic modeling, it is important for the researcher not to impose factor structure into the data, but instead allow for factor structure to emerge through the subsequent modeling process. To this end, it is recommended that the researcher keep interview questions as open-ended as possible. A rule of thumb for the creation of open-ended questions is to start each question with “how,” “why,” “what,” or “which” (Yin 2002). For more in-depth information on how to structure case study questions for subsequent analysis, the practitioner is referred to Yin 2002 (case study design best practices), Miles and Huberman 1994; Maxwell 2004 (conceptual framing and qualitative data analysis).

Step 7: Data collection

Data collection is an iterative process. While a case study protocol is needed to best prepare the researcher for data collection in the field, it is likely that many of the questions and procedures originally proposed in the case study protocol will need adjusting based on realities in the field. However, the more prepared a researcher is before collecting field data, the better. As such, the researcher is better off starting data collection with a *pilot study*, using the case study protocol to inform interview and survey questions, and then adjusting the questions based on the quality of the resulting data (Yin 2002). Data may take on the form of interviews, surveys, and observations, where possible data sources for the interviews and surveys may be: community water committee members, community households, municipality leaders, local organization leaders, and possibly local academic institutions. However, as each case will be different, the researchers must use his or her own discretion regarding data sources and collection types, referencing best practices from Yin 2002.

Step 8: Factor Structure

Assessment of factor structure is made possible through the creation and analysis of factor networks. There are two forms of data analysis required to create factor networks using the methods presented in this dissertation: coding and quantification (to identify emergent factors) and graphical modeling (to build factor networks).

Coding and Quantification: To identify model factors, transcribed interviews and observations must first be qualitatively coded, based on emergent themes and patterns identified by the researcher. The process of identifying emergent themes is iterative, requiring the researcher to continually update factor coding related to newly emerging themes, until all perceivable themes have been exhausted. An in-depth overview of the coding process and best practices is available in Miles and Huberman (1994). Once emergent themes are coded, the researcher must then aggregate these themes into factors. The extent to which factors are distilled down into factors is the decision of the researcher; however, as was mentioned previously in this dissertation, models (factor networks) that have a large number of factors are generally harder to interpret and trust. Factors are then quantified into binary format (yes or no) for the presence or absence of a particular factor within each sampled community context. For example, if Community A has issues with collecting household tariffs to finance water system maintenance, the code "Conflicts", would be given a "yes", or 1. The complete process of binary coding is presented in this dissertation (Chapter 4). Once each factor has been given a binary value, these data can then be analyzed with graphical modeling to identify factor networks.

Graphical Modeling: The process of building graphical models to infer factor networks begins by importing binary factor data for the sampled communities within the region of study into a graphical modeling software, such as R-Project. Then, these (discrete) data must be fit with a particular approximating model, such as a log-linear model or generalized linear model (GLM). The *dmod* function of *gRim* within R-Project may be used to fit a log-linear model to the data, designated as an *undirected graph*, since the direction of influence is assumed to be unknown. A best-fit model must then be found. The recommended method for model fitting is to use the *stepwise* function of *gRim* considering the statistical criterion as AIC and the type of analysis based on decomposable graphs to enable calculation of MLE with the penalty parameter, k, set to 2 for a true AIC model fit, using *backward selection.* Then, it is possible to use *igraph* to plot the emerging factor dependency to build the factor diagram. Each factor network may then be structurally analyzed as an adjacency matrix using some sort of centrality measure. The R-code used to build graphical models is shown in Appendix D.

Step 9: Structural Analysis

Once factor networks are built with graphical modeling, the process for identifying point centrality (factors) and graph centrality (entire factor network) follows the same algorithm as discussed in Step 5 and in Chapter 4 of this dissertation. The R-code used to perform structural analysis of factor networks is shown in Appendix D. The output from this analysis is an empirically derived set of impact factors that may be compared to the impact factors identified using SGMB.

Step 10: Strategic Action

At this final step of the SSA modeling process, the practitioner will have multiple forms of data and findings from which to guide some form of strategic action. From the SGMB process, the practitioner will have identified impact factors and dominant feedback mechanisms, both of which allow for the thoughtful identification of areas to allocate resources. From the EMB, both qualitative and quantitative data were analyzed with coding and graphical modeling to build empirical model structures, also allowing for the identification of impact factors. SGMB and EMB structures may then be compared and contrasted to improve confidence regarding the identified impact factors. While the SGMB team may not have been involved in the EMB process, it is recommended that this team be reassembled to assess SGMB and EMB structures.

If the modeling group is still not satisfied with the insight gained through SGMB and EMB, it may be necessary to either start the modeling process over, or to choose another framework with which to inform a decision. However, the insight gained through the first round of SGMB and EMB will likely be enough to further engage group modelers, and the process of performing a second round of SGMB will likely be sufficient to make a confident decision for action.