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Gaining Insight into Long-Term Functionality of Rural Water Services in Developing Countries: the Dynamic Interaction of Causal Factors

Jeff Walters, University of Colorado Boulder, USA
Amy Javernick-Will, University of Colorado Boulder, USA

Proceedings Editors
Paul Chan, The University of Manchester and Robert Leicht, The Pennsylvania State University

GAINING INSIGHT INTO LONG-TERM FUNCTIONALITY OF RURAL WATER SERVICES IN DEVELOPING COUNTRIES: THE DYNAMIC INTERACTION OF CAUSAL FACTORS

Jeff Walters,[1] Amy Javernick-Will[2]

ABSTRACT

Current approaches for the provision of rural water services (RWS) in developing countries appear unfit to adequately interpret and adapt to the dynamic and complex interactions of technical, social, financial, institutional, and environmental factors that often lead to premature project failure. System dynamic modeling or "systems thinking" has been employed successfully to model the behavior of complex and dynamic systems and could be a promising way to better understand how these factors interact as a system over time. The objective of this multi-method study was to develop theory regarding the dynamic causal interaction between these factors. Factors were identified using a systematic literature review of scholarly journals and journals published informally within the water sector. The study identified 157 factors that could affect the long term functionality (i.e. sustainability) of a rural water system in a developing country. These factors were aggregated into functional groups called "sustainability factors", including: Government, Community, External Support, Management, Financial, Environment & Energy, Technology Construction & Materials, and Water System Functionality. A panel of water sector experts was then assembled for a Delphi survey to determine the interaction and dynamic feedback mechanisms between these sustainability factors using a polarity analysis. A causal loop diagram (CLD) describing the dynamic nature of the system was constructed with the results from the Delphi survey. 101 unique feedback mechanisms involving water system functionality were identified within the CLD. Loop dominance was found using normalized influence scoring between sustainability factors and water system functionality. Anecdotal feedback mechanisms identified in literature were then used to compare and contrast those identified using influence scoring. The feedback mechanisms identified were largely dominated by two and three factor feedback systems, those containing some combination of Financial, Management and Community factors. Creating the aforementioned causal loop diagram served an important role in not only developing theory on the causal interactions between factors that affect long-term functionality of rural water infrastructure–but also in setting a crucial benchmark and guide for further quantitative modeling.

KEYWORDS: *Sustainability, Rural, Water, Modeling, Delphi*

[1]PhD Candidate, University of Colorado Civil Systems Engineering, Boulder Colorado, jeffrey.walters@colorado.edu.
[2]Assistant Professor & CEM Faculty Fellow, University of Colorado Construction Engineering Management, Boulder CO, amy.javernick@colorado.edu.

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, intervention attempts to sustainably lower these statistics have been unsuccessful. Studies have shown that more than 30% 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). Unfortunately, current approaches to plan for and evaluate the sustainability of rural water projects in developing countries are reductionist and static in nature, and thus, do not adequately consider, interpret and adapt to the dynamic interactions of technical, social, financial, institutional, and environmental factors that often influence project success or failure (Sara & Katz 1997, Sugden 2001, 2003). In order to create sustainable solutions to water poverty, these systemic and dynamic complexities must be considered.

A system dynamics modeling approach was chosen as a promising way to improve understanding of the dynamic complexities associated with sustaining long lasting functionality rural water services in developing countries. System dynamic modeling has the ability to go beyond the inherent limitations of linear and static models to consider the potentially confounding dynamic feedback mechanism between factors at play in a complex, interconnected system (Forrester 1962, Richmond 2001, Sterman 2000, Meadows 2008). The power of system dynamic modeling lies not only in its ability to understand the complex structure of influences that lead to a particular issue or behavior, but also as a way to learn from, adapt to, and plan for the unintended consequences that could result from a particular policy change or intervention (Vennix 1996, Pruyt 2013, Richmond 2001, Meadows 2008). Rather than continued reliance on static analysis, a system dynamics approach was chosen as a way to improve understanding by considering the dynamic interactions between political, social, technological and environmental influences that often hinder long term functioning of rural water services in developing countries.

POINT OF DEPARTURE

Literature within the international water development sector is rich with studies investigating the causes of water system failure in developing countries. For instance, literature has shown community based management plans 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, often water systems fail to respond to local needs, desires, and demands, leading to eventual abandonment of the water system (Chatterly 2012, Wateraid 2011). And, finally, a lack of harmonious coordination between donors, non-governmental organizations, and key stakeholders, coupled with inefficient use of resources, stifles effective capacity building of the community, government, and local institutions (Lockwood 2003, 2011). These examples 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 international water sector has focused on 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, Davis & Marks 2012), the feasibility of financial management schemes (Whittington 1990), user demand (Davis & Marks 2012, Whittington et al. 2008), supply chain management (Harvey & Reed 2007), and environmental resource management (Abramson et al

2011), to evaluate water service sustainability (Sugden 2003, Lockwood et al. 2003, Lockwood & Smits 2011, Godfrey et al. 2009, Godfrey et al. 2013, USAID 2013). While these studies have made significant progress in identifying the factors that can affect long-term functionality (i.e. sustainability) of rural water services, and some have combined these factors, the frameworks created to assess the interaction of these factors remain overly simplified and evaluate the sustainability of a water system through a process of scoring and linear superposition of these factors. Ultimately, this simplification of the interaction of factors leads to a limited understanding of sustainability and fails to consider the confounding feedback mechanisms that largely affect long term-term functionality of water services (Sara & Katz 1997, Sugden 2003, Lockwood et al. 2003).

Thus, the aim of this research is to investigate a means to evaluate potential feedback mechanisms that affect functionality of rural water services in developing countries. Specifically, the three primary questions this research addresses are:

Q1: What are the factors that affect long-term functioning of rural water services in developing countries?
Q2: How do these factors form an interconnected system?
Q3: What are the most important feedback mechanisms that influence long-term functionality?

RESEARCH METHODOLOGY

To answer these questions, we selected a multi-method research approach that culminates with system dynamic modeling. The requirements for system dynamic modeling guided the selection of research methods in the initial phases of this research, as described below. System dynamic modeling can take the form of qualitative or quantitative modeling, whereby qualitative system dynamic modeling often precedes quantitative modeling (Wolstenholme 1990, Vennix 1996). The goal of qualitative system dynamic modeling is to develop dynamic theory (theory of emergent feedback mechanisms) in the form of a causal loop diagram (CLD) which visually describes the causal structure hypothesized to drive the dynamic behavior of the system. In this case, dynamic behavior is manifested in the emergence of feedback mechanisms called "feedback loops". Since the aim of this research is to first hypothesize the feedback mechanisms that may potentially affect long-term functionality of rural water services, the research method focuses solely on the qualitative system dynamic modeling process.

The creation of dynamic theory will follow the three phase process shown in Figure 1, whereby each phase addresses one of the research questions. Phase 1 of the process entails clearly identifying and defining the factors that that will be used to describe the dynamic behavior of the system (RQ1). Phase 2 entails making distinctions regarding the influence between each factor (RQ2). Finally, Phase 3 entails analyzing the potential causal loops that exist within the CLD (RQ3). Due to the multi-method approach we present each Phase, including the method employed, and followed immediately by the results, in the proceeding sections.

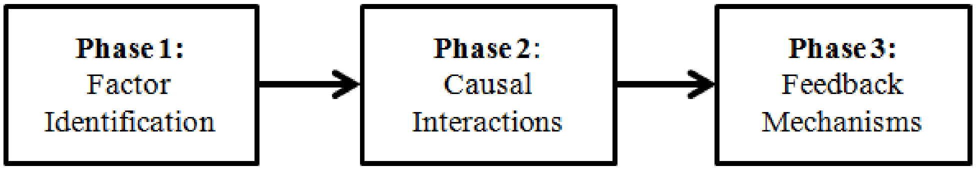

Figure 1: Overall Research Process

Phase 1: Factor Identification

To identify the factors used in the causal loop diagram (CLD), we performed a content analysis of 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”. Searching within informal literature archives was less systematic, and apart from searching within the International Water & Sanitation Centre (IRC) publications, the process was driven primarily by following references within these articles to seminal work on sustainability. The literature were analyzed by coding and aggregating recurring references 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). 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 project sustainability in developing countries. Articles that did not meet this requirement were excluded. Factors identified to have an effect on water system functionality were coded within NVivo. Finally, sustainability factors were grouped with affiliated categories 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, Shol & Tieje 2002).

The initial keyword search yielded 472 and 176 articles within scholarly journals and grey literature, respectively. From these, 97 articles were chosen for specific their applicability towards rural water project sustainability factors. These 97 articles yielded 157 unique references to factors that aided or hindered sustainability and functionality of a rural water system. These factors were then aggregated into the aforementioned sustainability factors, which included: Government, Community, External Support Management, Financial, Environment & Energy, Technology Construction & Materials, and Water System Functionality. Table 1 summarizes these sustainability factors, including a definition, the key sub-factors each factor includes, and the number of articles mentioned for each sub-factor.

Table 1: Affiliation group summary from 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 properly 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
	Cooperation	14	

	Post Const. Supp.	12	properly operate, maintain, monitor, and eventually replace the rural water system.
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 a community, external organization/ agency, or governing body to financially support the costs associated with the operation, maintenance and eventual replacement of the rural water system.
	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 RWS.
	Tech. Appropriateness	29	
	Construction Quality	9	
Environment & Energy	Resource Management	20	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.
	Source Protection	17	
	Energy Avail/Reliable	8	
Water System Functionality	Quality	18	The quality of the water as it compares to the country standards for drinking water quality
	Quantity	30	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	20	The duration of continuous operation of the water system without water shortages or break-downs
	Coverage	26	The availability of water services to users

Phase 2: Causal Interactions

A Delphi panel of experts was assembled in an attempt to reach consensus regarding the influence between the sustainability factors identified in Phase 1 of this study. The Delphi Method is a rigorous research technique for facilitating efficient group communication between geographically dispersed experts regarding underlying relationships among causal factors (Hallowell et al 2010, Turoff 1975, Gratch 2012, Vennix 1996). This is typically done through a multi-round survey whereby panelists are presented in each subsequent round with the aggregate group responses from the previous round in an attempt to facilitate consensus. A thoughtful selection of experts was considered critical to the quality of the study, as many researchers reference non-uniformity between expertise of panelists as a major weakness of the methodology (Hsu 2007). Thus, a 6-point criterion was used to select panelists, shown in Table 2 below, per recommendation of Hallowell et al. (2010). These criteria were created based upon the attribute desired for each panelist, highlighting most the panelist's experience and engagement in research on the topic of 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 using the criteria shown in Table 1 (Ludwig 1997, Hsu 2007). 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 a. 1975).

Table 2: The Criterion to Select the Expert Panel (6 points required for inclusion)

Points	Criteria
1 per article up to 3	Primary or secondary writer of a peer reviewed journal articles on sustainable rural water system and factors
1 per article up to 2	Primary or secondary writer of “gray” literature on sustainable rural water system and factors
1	Member or chair of a nationally recognized committee focused on sustainable
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 project 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 RWS provision

The Panelists were sent online survey questionnaires that asked 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 a good metric for general consensus in cases such as this, where panelist agreement is used as a viable indicator of consensus (Hwang 2004, Saldanha & Gray 2002, Cottam et al 2004, Islam et al. 2006). Using APMO each consensus limit between factors (factor A on B, C, D…etc), would be considered on a factor-by-factor basis. If APMO was less than 51 percent, the limit for consensus was automatically set at 51%, per the definition of “majority” (Gratch 2012). The equation for APMO is shown below.

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

Qualtrics was used to disseminate the survey electronically. In Round 1, the experts were acquainted with the objective of the study and given definitions for each of the factors. Each expert was then asked to indicate the polarity between each of the factors as well as the polarity of influence between the factors themselves including water system functionality. 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 will influence Factor B, either: (+) an increase in Factor A will cause an increase in Factor B (a direct relationship); 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 (an indirect relationship). Through this pair-wise analysis, called a “polarity analysis”, it was possible to systematically gain insight into the causal relationships between factors as a system.

The data from Round 1 were analyzed in Microsoft Excel using an individualized APMO consensus limit for each factor, as summarized in Table 3. Pair-wise 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. In Round 2, each panelist was asked to again make pair-wise comparisons regarding the influence between the factors that did not reach consensus in Round 1. In this round, however, panelists they were presented with the combined responses of the other panelists. Per typical Delphi protocol, this was to see if a panelist reinterpreted the questions based upon the responses from the other panelists.

In Round 1, consensus was reached on 27 of the 56 potential polarities of influence between the sustainability factors. The panelists were asked to, once again, rate the polarities that did not reach consensus (29) in Round 2. This round 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 causal loop diagram. 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). The results from each round are shown in Table 3.

Table 3: Delphi Round 1 and 2 Results

Influence Number	Influence Category	Influence Description	Round 1					Round 2					Final Consensus?
			+	0	-	Maj. %	APMO	+	0	-	Maj. %	APMO	
1		Gov - Func	21	2	0	91		------CONSENSUS------					yes
2		Com - Func	22	1	0	96		------CONSENSUS------					yes
3	Water	Ext - Func	16	5	1	73		17	4	1	77		no
4	System	Man - Func	21	1	0	95	90	------CONSENSUS------				82	yes
5	Functionality	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	Water	Func - Ext	3	13	4	65		2	18	2	82		yes
11	System	Func - Man	13	7	0	65	67	16	6	0	73	72	yes
12	Functionality	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	Ext - Man	10	6	4	50	53	18	3	1	82	65	yes
30	Support	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	Financial	Fin - Gov	9	9	1	47	56	15	7	0	68	58	yes
40		Fin - Com	20	1	0	95		------CONSENSUS------					yes
41		Fin - Ext	8	8	4	40		10	9	3	45		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	Environment & Energy	E&E - Gov	7	10	1	80	55	------CONSENSUS------				52	yes
46		E&I - Com	13	5	2	55		------CONSENSUS------					yes
47		E&E - Ext	3	12	3	70		------CONSENSUS------					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	Technology, Construction & Materials	TCM - Gov	4	16	0	56	59	5	17	0	77	68	yes
52		TCM - Com	9	11	0	65		------CONSENSUS------					yes
53		TCM - Ext	5	14	1	67		------CONSENSUS------					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

Phase 3: Feedback Mechanisms

A causal loop diagram (CLD) was created using the consensus results from Round 1 and 2 of the Delphi, shown in Figure 2. This CLD was then imported into the VENSIM system dynamic modeling software to systematically identify feedback loops that specifically influence water system functionality. It was possible to identify 101 unique feedback loops using a tool within the VENSIM software for systematic feedback loop identification. A simple example of one feedback mechanism from the diagram below is: Community influences Water System Functionality, which, in turn, influences Community. A full list of the causal loops identified in this CLD is shown in the Table 4. In this table, the different loops are categorized based on their combination of factors (rows), and the length of the feedback loop causal chain (columns). For example, the aforementioned feedback loop: Water System Functionality-Community-Water System Functionality (WSF-Com), is displayed in Table 4 as combination number 2, loop length 1.

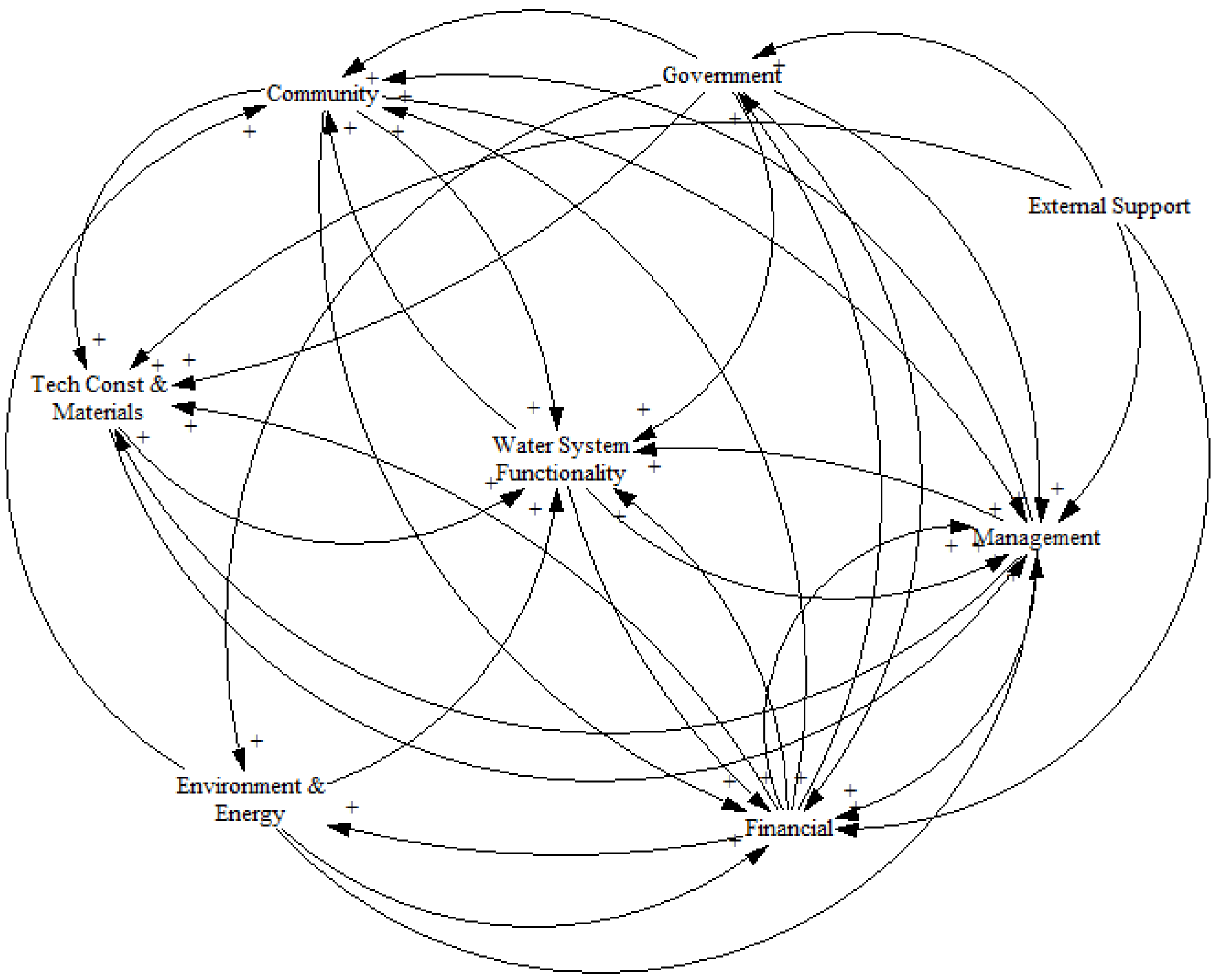

Figure 2: Causal loop diagram from the Delphi study

Table 4: Distribution of loop combinations based on loop factor length

		LOOP FACTOR LENGTH					
	No	2	3	4	5	6	7
COMBINATION	1	WSF-Man	WSF-Man-TCM	WSF-Man-Fin-E&E	WSF-Man-Fin-Gov-Com	WSF-Fin-Gov-E&E-Com-TCM	WSF-Fin-Gov-E&E-Com-Man-TCM
	2	WSF-Com	WSF-Man-Com	WSF-Man-Fin-Com	WSF-Fin-E&E-Man-Com	WSF-Fin-E&E-Com-Man-TCM	WSF-Fin-Gov-E&E-Com-TCM-Man
	3	WSF-Fin	WSF-Fin-E&E	WSF-Man-Fin-Gov	WSF-Man-Com-Fin-TCM	WSF-Man-Fin-Gov-E&E-Com	WSF-Com-Fin-Gov-E&E-Man-TCM
	4		WSF -Fin-Man	WSF-Man-Com-TCM	WSF-Com-Fin-Man-TCM	WSF-Com-Man-Fin-Gov-E&E	WSF-Man-Fin-Gov-E&E-Com-TCM
	5		WSF-Fin-Gov	WSF-Fin-E&E-Man	WSF-Fin-Gov-TCM-Man	WSF-Com-Fin-E&E-Man-TCM	WSF-Fin-Gov-E&E-Com-Man-TCM
	6		WSF-Man-Fin	WSF-Fin-Com-Man	WSF-Man-Fin-E&E-Com	WSF-Com-TCM-Man-Fin-E&E	WSF-Com-TCM-Man-Fin-Gov-E&E
	7		WSF-Com-TCM	WSF-Fin-Gov-TCM	WSF-Fin-Man-Com-TCM	WSF-Man-Com-Fin-Gov-E&E	
	8		WSF-Com-Fin	WSF-Man-Com-Fin	WSF-Fin-Gov-E&E-Com	WSF-Man-Fin-Gov-Com-TCM	
	9		WSF-Fin-Com	WSF-Com-TCM-Man	WSF-Man-Com-Fin-Gov	WSF-Fin-Gov-E&E-Man-TCM	
	10		WSF-Fin-TCM	WSF-Com-Fin-E&E	WSF-Fin-E&E-Man-TCM	WSF-Fin-Gov-Com-TCM-Man	
	11		WF-Com-Man	WSF-Fin-Gov-Man	WSF-Man-Com-Fin-E&E	WSF-Com-Fin-Gov-Man-TCM	
	12			WSF-Com-Fin-Man	WSF-Fin-Gov-Man-TCM	WSF-Com-Man-Fin-Gov-TCM	
	13			WSF-Fin-TCM-Man	WSF-Fin-Com-Man-TCM	WSF-Man-Com-Fin-Gov-TCM	
	14			WSF-Fin-Man-Com	WSF-Fin-Gov-Com-TCM	WSF-Fin-E&E-Man-Com-TCM	
	15			WSF-Man-Fin-TCM	WSF-Fin-TCM-Man-Com	WSF-Fin-Gov-TCM-Man-Com	
	16			WSF-Fin-Man-TCM	WSF-Fin-E&E-Com-Man	WSF-Com-TCM-Man-Fin-Gov	
	17			WSF-Com-Man-Fin	WSF-Fin-Com-TCM-Man	WSF-Fin-E&E-Com-TCM-Man	
	18			WSF-Com-Fin-TCM	WSF-Man-Fin-Gov-TCM	WSF-Man-Fin-E&E-Com-TCM	
	19			WSF-Fin-Gov-Com	WSF-Man-Fin-Gov-E&E	WSF-Fin-Gov-Man-Com-TCM	
	20			WSF-Fin-Gov-E&E	WSF-Com-Man-Fin-Gov	WSF-Com-Fin-Gov-E&E-Man	
	21			WSF-Fin-E&E-Com	WSF-Com-Fin-E&E-Man	WSF-Fin-Gov-Com-Man-TCM	
	22			WSF-Fin-Com-TCM	WSF-Com-Man-Fin-E&E	WSF-Com-Fin-Gov-TCM-Man	
	23			WSF-Com-Man-TCM	WSF-Fin-Gov-E&E-Man	WSF-Fin-Gov-E&E-Man-Com	
	24			WSF-Com-Fin-Gov	WSF-Com-Fin-Gov-TCM	WSF-Fin-Gov-E&E-Com-Man	
	25				WSF-Com-Fin-TCM-Man		
	26				WSF-Fin-Gov-Man-Com		
	27				WSF-Com-TCM-Man-Fin		
	28				WSF-Com-Fin-Gov-E&E		
	29				WSF-Fin-Gov-Com-Man		
	30				WSF-Com-Fin-Gov-Man		
	31				WSF-Man-Fin-Com-TCM		
	32				WSF-Fin-E&E-Com-TCM		
	33				WSF-Com-Man-Fin-TCM		

WSF = Water Sysetm Functionality; Gov = Government; Com = Community, Ext = External Support; Man = Management; Fin = Financial; E&E = Environment & Energy; TCM = Technology Material & Consruction

DISCUSSION:

Several compelling findings may be inferred from the results of this study. Rounds 1 and 2 of the Delphi showed all existing influences were positive. This indicates the resulting feedback loops are all reinforcing and would therefore lead to a system behavior that is either one of growth (increasing), decay *(*decreasing), or a combination of both depending on the dominance of the loops over time. In this case, dominance refers to the temporal state where a particular feedback mechanism is dominating system behavior. In other words, certain feedback mechanisms can dominate the behavior of a system at one point in time, and later be overpowered by a different feedback mechanism. In the context of a rural water system, a reinforcing feedback loop could imply water services that are increasing or decreasing in functionality over time depending, in this case, on which of the 101 feedback mechanism dominate throughout the life of the system. This observation matches the general trend of rural water system functionality (waterpoints) found in a study by WaterAid Tanzania in 2009, where the trend was a drastic decrease in functionality over 2 to 7 years, as shown in Figure 3 (WaterAid Tanzania 2009). Additionally, the results showed the majority of potential feedback mechanisms were between 3 and 5 factors long; that is, the feedback loop "chain" was made of 3 to 5 factors (see Table 4 above). That even this highly simplified system representation, which uses only 8 variables to describe rural water system functionality, yielded these complex feedback mechanisms is compelling evidence for why current reductionist and static methods improperly treat water system sustainability.

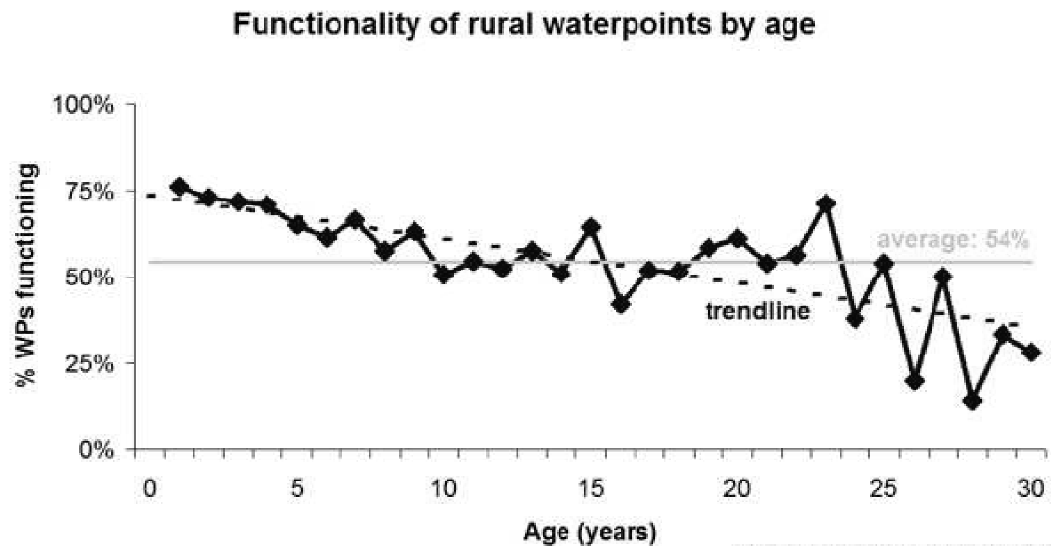

Figure 3: Functionality vs. Time Data from WaterAid 2009 Tanzania Water Point Study

In light of these points, however, the question still remains: which of the 101 feedback mechanisms influences most long-term water system functionality? Indeed, the polarity analysis conducted in the Delphi study, while providing useful insight into the dynamic behavior of the system, does not explicitly allow for the prioritization of feedback mechanisms in terms of loop dominance. Perhaps it is possible, however, to infer loop dominance by regarding the relative "level of influence" of the factors themselves whereby each factor is given an interaction score based on the number of influences it has on, and with, other factors. An example of this possible interaction scoring scheme is shown in Table 5. These scores assume each influence is equally weighted. It might then be possible to prioritize the dominance of the causal loops based on this scoring scheme by summing and then normalizing the factor scores within each feedback mechanism based on the number of factors within the loop. For example, using the individual factor scores from Table 5 for feedback loop combination 12, length 3 in Table 4 (WSF-Com-Fin-Man), the combined score for this loop would be 10 (9 + 8+ 12 + 11)/4. Based on these assumptions, the top five loops are shown in Table 6.

Using this ranking scheme, the most dominant feedback mechanisms primarily involve between 2 and 4 sustainability factors, implying that higher order mechanisms would be most influential. Literature traditionally points to single factor loops as the leading cause of project failure (i.e. poor community management or poor governance). However, it may be possible that the single factor failure mechanisms identified in literature were actually a result of a systemic combination of underlying issues that were not considered in a static analysis. For example, poor community management (Community), while being the apparent cause of system failure due to improper system maintenance (Management), could have be caused by improper coordination by the government or institution (Government and External Support) to train the community as a result of municipal budget cuts (Financial). Additionally, an inability to acquire quality materials for the proper maintenance of the system (Technical, Construction & Materials) may lead to a water system that fails to operate properly over time (Water System Functionality), leading to an increasing level of disillusionment of community households thereby affecting the willingness for households to pay their monthly user tariff (Financial), and so on. Examples such as these demonstrate the importance of understanding the underlying feedback mechanisms that potentially cause an emergent outcome such as water system failure. Because these were obtained based upon expert opinion, however, these feedback mechanisms need to be validated based on empirical evidence.

Table 5: Factor influence scoring

	Interaction		
Sustainability Factor Category	No. Influences	No. Influenced	Interaction Score
Government	5	2	7
Community	3	5	8
External Support	4	0	4
Management	4	7	11
Financial	6	6	12
Enviro. & Energy	4	2	6
Tech., Const, & Mat.	2	5	7
Wat. Sys. Functionality	3	6	9

Table 6: Top 5 Dominant Loops based on influence scoring

Combination No.	**Length**	**Loop Description**	**Rank**	**Normalized Score**
4	3	WSF-Man-Fin	1	10.7
3	2	WSF-Fin	2	10.5
12	4	WSF-Com-Fin-Man	3	10
1	1	WSF-Man	4	10
3	4	WSF-Man-Fin-Gov	5	9.8

While the systematic literature review in this study primarily found examples where water system failure was attributed to a single cause, the Global Water Initiative (GWI) (2014) recently completed a 5 year case study in Central America that made several claims regarding potential "cycles" that influenced failure or success of rural water systems. In this study, GWI articulated the following feedback loop for project failure shown in Figure 4 (Global Water Initiative 2014). This feedback loop reads: "poor services causes users to be less willing to pay their monthly user fees, which decreases the capacity of the water user association (WUA) to maintain the system and collect future tariffs which then leads to the community not trusting the WUA which leads to an indignant posture within the community and among the WUA to maintain the system which leads to poor services". It is possible to distill this 6 factor chain down to 3 key factors in conjunction with Water System Functionality using the terminology from this study. The loop that emerges is combination 12, loop length 3 shown in Table 4: Water System Functionality – Community – Management – Financial (WSF-Com-Man-Fin). This comparison between the feedback mechanism articulated within the GWI case study and those identified through the polarity analysis, helps validate the results of this study.

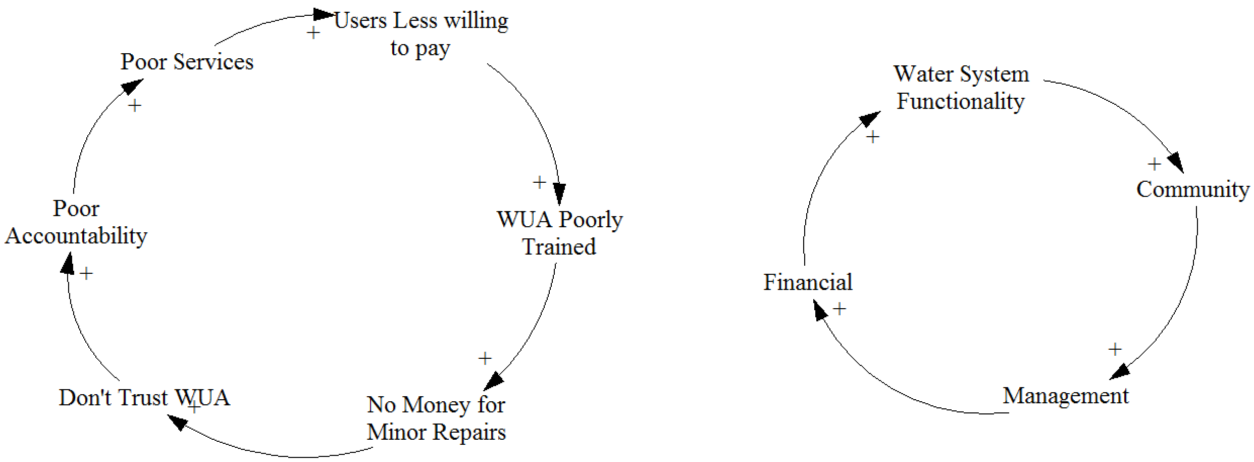

Figure 4: GWI Feedback Mechanism for Failure (left); combination 12, loop length 3 from Table 4 (right)

Similarly, GWI recommends a positive cycle to combat the cycle for failure, shown in Figure 5. In this cycle, "Empowered citizens will pay for their services which will increase water service provider capacity which will increase the ability to maintain the system which will result in good service provision", again matches the cycle combination number 12, loop length 3 from Table 4 (GWI 2014). While this shows the destructive feedback mechanism identified before, if reversed, it can instead be hypothesized to lead to high system functionality over time. It also seems logical that the loops which have the greatest dominance would be those that include Management, Financial, and Community factors. Based on this observation, feedback mechanisms that have a high level of these three factors would ensure long term water system functionality. Conversely, any decrease in any or all of these factors would seemingly lead to a considerably fast cascading decrease in water system functionality, as is typically seen in water sector literature.

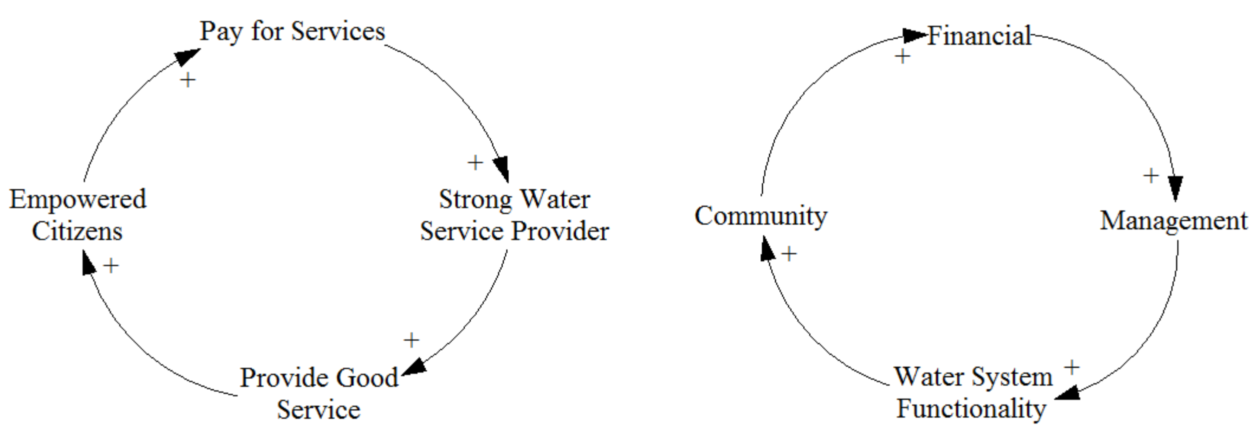

Figure 5: GWI feedback mechanism for success (left); combination 12, loop length 3 from Table 4 (right)

STUDY LIMITATIONS

As with any study, this research has limitations associated with the research methodology employed. In the content analysis, the literature review, while systematic, was likely not fully exhaustive and could have left out potential causal factors in the coding process. Additionally, the process of aggregating factors into “sustainability factors” conceivably could conceal those factors which were 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 impact the construct validity of the study.

The Delphi study also had potential for errors due to the limitations inherent in the methodology itself. Responses from panelists could be biased due to a misinterpretation of the question context. There were many instances where panelists conveyed their frustration in being asked to generalize water system functionality from a “high level”, and often desired firmer contextual grounding from which to indicate the influences between factors. This frustration may have resulted in panelists taking less care in selecting influences, and could have caused the results to be flawed, thereby affecting the internal validity of the study.

Conducting a polarity analysis between factors only served to identify a list of potential feedback mechanisms, and did not allow for prioritization of these mechanisms based on loop dominance. Even if it were possible to reach consensus on all 56 potential influences, this would still merely identify potential feedback mechanisms without diving further into theory regarding the dominant mechanisms hypothesized to affect rural water system functionality. The limitation of a polarity analysis was circumvented in the paper through the use of interaction scoring and qualitative evidence from literature to hypothesize loop dominance. For example, while the GWI case study allowed for some external validation of feedback mechanisms identified in the causal loop diagram and loop combinations in this study (Figure 2 and Table 4), it must be considered that the management scheme investigated by GWI study was based on the philosophy that community empowerment (i.e. community based management) was the preferred management scheme for the sustained functionality of rural water services. This might explain why Community was one of the three most influential factors. Similarly, the combined opinion from the expert panelists could have been biased towards a particular type of management strategy based on current sector wide opinion (government vs. external support vs. community based), which would explain why certain factor influences reached consensus so quickly, while others did not (for example, External Support).

A more rigorous attempt to identify feedback mechanisms must be employed in future studies whether through validating feedback mechanisms in case studies or additional Delphi expert panels of key stakeholders performed in a multitude of different contexts (e.g. country, technology, management scheme). Additionally, investigation into other predictive tools such as Cross Impact Analysis (CIA), could also allow for improved interpretations of feedback mechanisms from similar Delphi data.

Certainly the weak point of this study was the subjectivity in assumptions taken by both the authors as well as the expert panelists regarding factor interaction and causal loop dominance. Developing a way to navigate this subjectivity, while producing meaningful results, will be paramount for future studies.

CONCLUSION & STUDY IMPLICATIONS

Current approaches to plan for, and assess, sustainability of rural water systems rely on static and linear frameworks that inadequately consider the systemic and dynamic interaction of technical, social and environmental factors that often lead to project failure. Thus, the aim of this study was to investigate a way to improve understanding of the dynamic and systemic interaction of these factors. To accomplish this, the study identified factors that influenced rural water system functionality from a content analysis of scholarly journals and journals published informally within the water sector. These factors were then aggregated into "sustainability factors", and assembled a Delphi panel to determine the influence of each factor on the other factors and water system functionality. When the results were modeled, a causal loop diagram (CLD) was constructed. The CLD identified 101 unique feedback mechanisms which could potentially influence water system functionality. While the causal loop diagram did not explicitly allow for the prioritization of the 101 feedback mechanisms in terms of loop dominance, it was possible to make distinctions regarding the general makeup of the most dominant loops using factor influence scoring and anecdotal references in case study literature. Based on these methods and assumptions, the most dominant loops were found to entail a combination of Management, Financial, and Community factors. Practically, this implies that maintaining good management, good financial planning, and an enabling environment for proper community use and repair of the system, could potentially increase sustained functionality of a rural water system. Conversely, this also implies that a decrease (or absence) in any of these three factors could lead to a cascading decrease in the other factors and ultimately lead to poor functionality of the water system.

While this methodology has limitations, there are intrinsic benefits to engaging in qualitative modeling of this type as a way to articulate the structuring of a problem (Alarcon & Ashley 1998). As Godet 1986 remarks, this 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." (Godet 1986). To that end, this research presents an initial framework for how future research of this type may be conducted using expert opinion for the production of systems based knowledge and understanding of sustainability of rural water infrastructure in developing countries. In addition it hopes to contribute valuable knowledge to inform the international water sector about sustainable solutions to rural water poverty. This might be accomplished in the future by extending sustainability frameworks for rural water project assessment, which are currently linear and static, into a dynamic system-based paradigm of decision making situated at the complex science-technology-society nexus. More specifically these efforts might include creating quantitative system dynamic models to simulate and explore how certain factors interact to induce dynamic trends in water system functionality within different country and cultural contexts.

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