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Long-term functionality of rural water services in developing countries: A system dynamics approach to understanding the dynamic interaction of causal factors

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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 systems dynamic 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 loops that contained some combination of the factors: Water System Functionality, Community, Financial, Government, Management, and Technology. These feedback mechanisms were then scored and prioritized, with the most dominant feedback mechanism identified as Water System Functionality – Community – Finance – Management. This research offers insight into the dynamic interaction of factors impacting sustainability of rural water infrastructure through the identification of these feedback mechanisms and makes a compelling case for future research to longitudinally investigate the interaction of these factors in various contexts.

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Introduction

In the developing world, over 768 million people are without access to safe drinking water, 83% of which live in rural communities[1]. However, despite well-intended efforts, many intervention attempts to sustainably lower these statistics have been unsuccessful. Studies have shown that between 30% to 50% of rural water projects, whether water systems or wells, fail between 3 and 5 years following construction[2]. Sustainability is often hindered as a result of the complex and dynamic interactions of technical, social, financial, institutional, and environmental factors that influence project success or failure over time[3-5]. Therefore, in order to create long-lasting solutions to water poverty, the systemic and dynamic interaction between these factors 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-term functionality of rural water services in developing countries. System dynamics modeling enables the dynamic analysis of factors in the form of *causal loops* or *feedback mechanisms* that are used to understand what drives a particular emergent outcome, such as the success or failure of a rural water project[6-9]. The power of system dynamic modeling lies not only in its ability to understand the complex structure of factors and influences that lead to a particular problem, but also as a way to learn from, adapt to, and plan for unintended consequences that could result from a particular solution[7,9-11]. Literature within the international water development sector is 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[12], with wells breaking down frequently due to poor maintenance or insufficient water supplies caused by seasonal fluctuations in water levels[13]. In addition, water systems often fail to respond to local needs, desires, and demands, leading to eventual abandonment of the water system[14,15]. 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[16-20]. 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 international water development sector has created evaluation frameworks which 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[21,22] , the feasibility of financial management schemes[23], user demand and willingness to pay[23,24] , supply chain management[25,26], and environmental resource management[27-28] , and to evaluate water service sustainability[29-31]. These studies have identified the factors that can affect long-term functionality of rural water services through static indicators. However, while these studies have made significant intellectual contributions, evaluating the interaction of factors in this static way may lead to a limited understanding of sustainability by not fully considering their dynamic interaction[3,5,16] . Thus, the aim of this study was to investigate a methodology to extend existing knowledge on sustainable rural water service provision by considering the dynamic interaction of factors in the form of feedback mechanisms. By including these dynamic and systemic interactions, this study aims to provide motivation for future research focused on finding solutions and remedies to rural water issues that are systemic in nature.

Sustainability. To improve knowledge on sustainability of rural water infrastructure in developing countries, we must first clarify our definition of "sustainability". To adequately plan for and maintain rural water systems that are sustainable, the dynamic complexities between factors that often cause project failure must be considered. In this case the term "dynamic complexity", as defined by Peter Senge[32], is used to describe situations where "cause and effect are subtle, and where the effect over time of a particular intervention strategy is not obvious". Certainly, in the context of planning rural water projects or programs, the cause and effects of failure are often complexly intertwined and not obvious". Thus, sustainability is best elucidated in processed-based terms[33-38]. This explicitly requires the holistic systems-based integration of social, political, technical and environmental influences that are present in rural water system operation and maintenance, to create effective and adaptable policy and management systems[16]. Thus, in the context of providing sustainable rural water services, planning largely becomes a process of interpreting, and adapting to the dynamic interaction of factors that influence long-term functionality.

System Dynamics Modeling. System dynamics modeling is a process used to describe and simulate dynamically complex issues through the structural identification of closed-system feedback mechanisms that drive system behavior[7-10]. Following its inception in 1961 by Michigan Institute of Technology (MIT) professor, Jay Forrester, system dynamic modeling has been used for a wide range of applications. Specifically, there is a long tradition of using system dynamics to study public management issues[10] including public health[40,41] , energy and the environment[34,42] , social welfare (i.e. modeling the war on drugs)[8,43] , security[44], complexities present within economics and enterprises[6,8], and sustainable development[34,35,45] .

The efficacy of system dynamic modeling to describe a complex problem is predicated on the notion that closed-system interaction (feedback mechanisms) between factors dictates system behavior[6,9]. This implies that instead of problems being a result of single root-causes, the problem in fact may be caused by the endogenous interaction of factors interacting as a system[9]. System dynamic modeling thereby offers a way to understand the systemic nature of complex problems, and in turn, offers a way to formulate solutions that are also systemic in nature. Thus, a system dynamics modeling approach is well-suited for this research as a way to both identify the systemic and dynamic interaction between factors that cause the failure of rural water system functionality, as well as enabling the formulation of possible solutions.

Thus, the research methods employed in this study are guided by the system dynamic modeling process that entails identifying factors that influence long-term functionality of rural water infrastructure and their dynamic interaction in the form of feedback mechanisms. The dynamic causal interaction between these identified factors in developing countries were found using the opinion of water sector experts who participated in a Delphi study and survey. This paper presents the methods employed by this research, along with results, findings and insight for future studies.

Method

System dynamic modeling can take the form of qualitative or quantitative modeling, whereby qualitative system dynamic modeling often precedes quantitative modeling[11,39] . The primary objective of qualitative system dynamic modeling is to develop dynamic theory, traditionally 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 manifests in the emergence of feedback mechanisms often called “feedback loops”, where a feedback loop is a causal chain of two or more factors that reconnects to influence each factor in succession over time[10]. Since the aim of this study was to hypothesize the feedback mechanisms that affect long-term functionality of rural water services, this research focused solely on the qualitative system dynamic modeling process.

The creation of dynamic theory in the form of a CLD followed a three-phase process. Phase 1 entailed identifying and defining the factors that were used to describe the dynamic behavior of the system, by conducting a systematic literature review. Phase 2 involved making distinctions regarding the “polarity of influence” and “strength” between each factor from a panel of water sector experts using 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.

Phase 1: Factor Identification. To identify the factors used in the 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”. 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. 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[46] . 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[47,48] .

The initial keyword search yielded 472 articles within scholarly journals and 176 informal 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, and is not to be confused as the emergent outcome of long-term functionality.

Table 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[8]. 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 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 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 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 rural water system.
	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 system break-downs
	Coverage	26	The availability of water services to users

Phase 2: Causal Interaction. Two complimentary methodologies were employed in Phase 2 to ascertain two distinct causal characteristics between sustainability factors. First, a polarity analysis was conducted using the input from experts to characterize the dynamic influence (either indirect or direct) between factors. Second, a cross impact analysis (CIA) was

employed using input from the same group of experts to characterize the strength between factors. The rest of this section outlines these methods.

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[11,49-51]. 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 on a series of themes. Polarity of influence relates to the dynamic nature of pair-wise 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 pair-wise polarity of influence between each of the factors provides 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[52]. Thus, a 6-point criterion was used to select panelists, shown in Table 2, per recommendation of Hallowell et al. (2010)[49]. 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 using the criteria shown in Table 2[52,53]. 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[54].

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 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[55-58]. Using APMO each consensus limit between factors (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[51] . 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 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. 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. 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 pair-wise 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 typical Delphi protocol[51], 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 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). A causal loop diagram (CLD), created using the consensus results on factor influence from Round 1 and 2 of the Delphi, is shown in Figure 1.

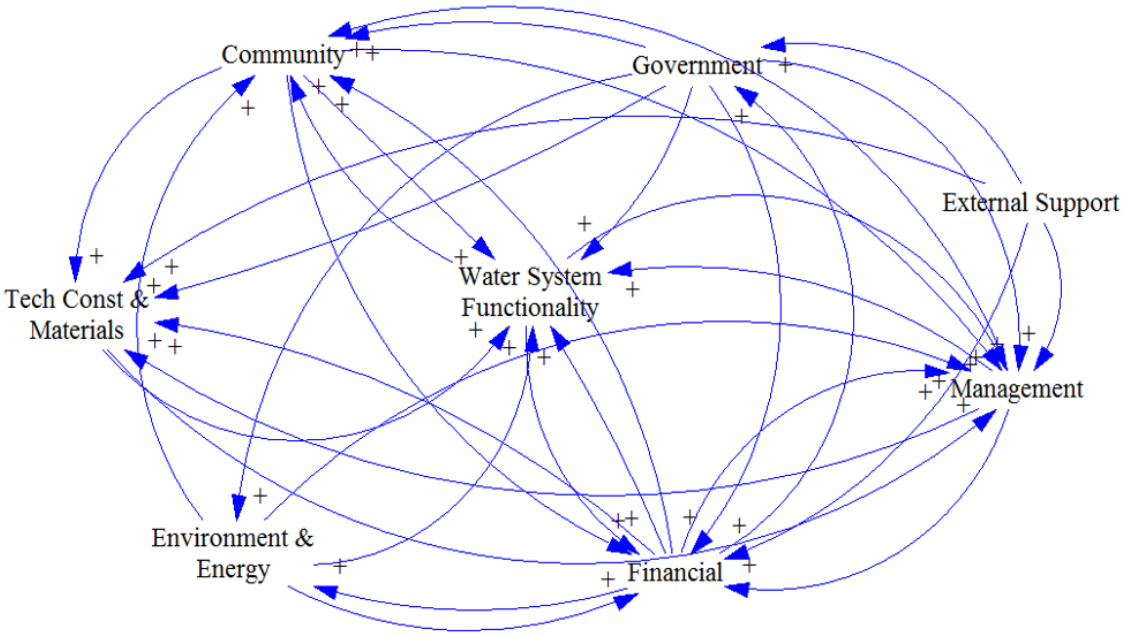

Figure 1. Causal loop diagram from the polarity analysis

Factor Strength: Cross Impact Analysis. 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 1. This objective was accomplished using Cross Impact Analysis. Performing a Cross Impact Analysis entails systematically defining the strength between system factors through the creation of an “impact matrix” which organizes the pair-wise interaction strength between these factors[50,] . 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)[59-62].

Expert responses on causal strengths had a wide range of variation. Because of this, these strengths were ascertained using the 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 3. Impact Matrix from Expert Cross Impact Survey

	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 causal loop diagram (CLD) (Figure 1) was imported into the Ventana Systems Inc.'s VENSIM system dynamic modeling software (www.Vensim.com) to identify feedback loops that influenced water system functionality using the program's "loop" tool. Combining interactions identified in the polarity analysis and CIA, it was possible to identify 101 unique feedback mechanisms that influence the factor Water System Functionality -- in such a way so as to influence long-term water system functionality

The question remains, which of the 101 feedback mechanisms most influences long-term water system functionality? To address this question, the study used factor influence ranking with the Cross Impact Analysis (CIA) data to identify dominant feedback mechanisms[59] . Using the CIA impact matrix created in Phase 2, loop strength was calculated by summing pair-wise influence scores for each factor within each causal loop. Loop scores were normalized based on the number of factors within the loop to enable comparison. For example, WSF-Com-Fin-Man from the impact matrix was calculated as (3 + 2 + 3 + 3)/4 = 2.75. The feedback loops with normalized scores of 2.4 and above are shown in Table 4.

Table 4. Top-5 normalized ranked loops based on direct influences

Loop 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

Results and Discussion

Several compelling 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 loops are all “reinforcing” and would likely 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 the context of a rural water system, a reinforcing feedback loop could imply water services that are increasing in functionality, or decreasing 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[63]. These examples support the inferred dynamic nature found using the CLD (Figure 1).

The 32 dominant feedback mechanisms from the CIA were found to contain six sustainability factors—Water System Functionality; Community; Financial; Government; Technology, Construction, and Materials (TCM); and Management—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 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.

These 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[15,64-71]. Additionally, there are many proponents for a framework that involves the community in managing the operation and maintenance of the water system[5,15,65,72] . Conversely, many experts in the literature believe 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[16,73]. Existing research also critically analyze 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[24,67,74]. Additionally, a recent study by Davis (2014) explicitly tied together the affect Water System– Functionality–Community–Financial–Management has on rural water system sustainability in Central America[75]. This past work offers great support for the factors, and the nature of their causal interaction, identified in the dominant feedback mechanism found in this study.

However, the top rank loop (Water System– Functionality–Community–Financial–Management) is only one of 31 other top-five ranked feedback mechanisms found in this study, many of which also included the factors: Government and TCM (see Table 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 loop WSF-Fin-Gov-Man, could conceivably be more dominant in a context where the management (operation and maintenance) was instead the responsibility of the local government. This provides a intriguing case for additional research efforts that elaborate on feedback mechanisms within different contexts (e.g. country, technology, management scheme). With the insight gained by these data, it may then be possible to develop quantitative models to simulate, explore, and learn more about the 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[76]. As Godet[47] 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” (pp. 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[7]. 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 failure will help enable rural water projects and programs to 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” conceivably 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. Responses from panelists may have been skewed due to the particular interpretation of the question context, given the inability for panelists to resolve confusion in a group setting. There were many instances where panelists conveyed the difficulty in generalizing water system functionality from a "high level", and often desired firmer contextual grounding from which to indicate the influences between factors. Additionally, an unavoidable limitation of this study was the subjectivity in assumptions taken by both the authors as well as the expert panelists regarding factor identification, interaction and feedback loop dominance. Thus, developing a way to better navigate this subjectivity, while producing meaningful results, will be paramount for future studies.

References

(1) Joint Monitoring Program (JMP). Progress on Sanitation and Drinking Water: Update 2013. *UNICEF and The World Health Organization*. WHO Library Catalogue, **2013**.

(2) WASH Sustainability Charter **2013**. Sustainablewash.org

(3) Sara, J; and Katz, T. Making Rural Water Supply Sustainable. *World Bank (WB), Water and Sanitation Program (WSP),* Washington, DC **1997**.

(4) Sugden, S. The Community Based Rural Water Supply, Sanitation and Hygiene Education Implementation Manual – Is it working*? WaterAid Malawi* **2001**, Private bag 364, Lilongwe 3, Malawi.

(5) Sugden, S. (2003). Indicators for the water sector: example from Malawi. *WaterAid Reporting* **2003**. sustainability-framework.pdf

(6) Forrester, J. Industrial Dynamics. *Productivity Pr.* **1962**

(7) Richmond, B. An Introduction to Systems Thinking. *High Performance Systems,* Inc. STELLA. **2001**.

(8) Sterman, J. Business Dynamics: Systems Thinking and Modeling for a Complex World. *McGraw-Hill/Irwin* **2000**.

(9) Meadow, D. Thinking in Systems: A Primer. *Chelsea Green Publishing*, **2008**.

(10) Pruyt, E. Small System Dynamics Models for Big Issues: Triple Jump Towards Real-World Dynamic Complexity. *TU Delft Library*, Delft, The Netherlands, **2013**. Version 1.0.

(11) Vennix, J. Group Model Building: Facilitating Team Learning Using System Dynamics. *Wiley, 1st edition*, **1996**.

(12) International Water and Sanitation Centre (IRC). Triple-S Briefing: Providing Reliable Rural Water Services That Last. **2009**. http://www.aguaconsult.co.uk/current-projects/sustainable-services-at-scale/

(13) UNICEF Sierra Leone. Sierra Leone Waterpoint Report. Review Version – June 26, 2012. *Sierra Leone Ministry of Energy and Water Resources* **2012.**

(14) Chatterly, C. Identifying Pathways to Sustainable Sanitation Services in Low-Income Schools. *Doctoral Dissertation*, **2012**. University of Colorado, Boulder

(15) WaterAid. *Sustainability Framework.* **2012** http://www.wateraid.org/~/media/Publications/

(16) Lockwood, H.; Bakalian, A.; Wakeman, W. Assessing Sustainability in Rural Water Supply: The Role of Follow-up Support to Communities. *Literature Review and Desk Review of Rural Water Supply and Sanitation Project Documents*, Britain **2003**.

(17) Lockwood, H.; Smits, S. Supporting Rural Water Supply: Moving Towards a Service Delivery Approach. *Practical Action Publishing Ltd*, **2011**.

(18) Baumann, E.; Danert, K.. Operation and Maintenance of Rural Water Supplies in Malawi. O&M Study. *Swiss Resource Centre and Consultancies for Development*, **2008**.

(19) Furgeson A.E.; Mulwafu, W.O. (2004). Decentralization, Participation, and Access to Water Resources in Malawi. *Collaborative Research Support Program*, **2004**. BASIC CRSP. Department of Agricultural and Applied Economics. University of Wisconsin-Madison.

(20) Nyirishima, R.; Mukasine, B. Multi-stakeholder platform for sustainable WASH Services: Lessons from Rwanda. *SNV Netherlands Development Organisation*, **2011**.

(21) Narayan, D. Participatory Evaluation: Tools for Managing Change in Water in Sanitation. *World Bank* Technical Paper Number 207, **1995**.

(22) Davis, J., & Marks, S. (2012). *Does User Participation Lead to Sense of Ownership for Rural Water Systems: Evidence from Kenya.* World Development. 40 (8) 1569-1576.

(23) Whittington, D. Estimating the Willingness to Pay for Water Services in Developing Countries: A Case Study of the Use of Contingent Valuation Surveys in Southern Haiti. *Economic Development and Cultural Change*, University of Chicago Press, **1990** 38(2), 293-311

(24) Abramson, A.; Becker, N., Garb, Y.; Lazarovitch, N. Willingness to pay, borrow, and work for rural water improvements in developing countries. *Water Resources Research*, **2011** (47) W11512.

(25) Harvey, P.; Reed, B. Community-managed water supplies in Africa: sustainable or dispensable? *Oxford Press and Community Development Journal*. **2007**.

(26) Harvey, P.; Reed, B. Rural Water Supply in Africa: Building Blocks for Hand Pump Sustainability. *Water, Engineering and Development Centre* (WEDC) **2004**, Loughborough University.

(27) Abrams, L.; Palmer, I.; Hart, T. Sustainability Management Guidelines for Water Supply in Developing Communities. *Department of Water Affairs and Forestry* **2006**, South Africa.

(28) Jones, S.; Silva, C. A practical method to evaluate the sustainability of rural water and sanitation infrastructure systems in developing countries. Desalination, **2009** 248 500-509.

(29) Godfrey, S.; Muianga, A.; Fernandez, P.;Sousa M.,L. (2009). Sustainability Check: A monitoring tool for the sustainability of rural water supplies. Conference Paper. *34th WEDC International Conference*, Addis Ababa, Ethiopia, **2009**.

(30) Godfrey, S.; Van der Velden, M.; Muianga, A.; Xavier, A. Sustainability Check: five years annual sustainability audits of water supply and open defecation free status in the One Million Initiative, Mozambique. *UNICEF Mozambique*, **2013**.

(31) United States Agency for International Development (USAID). *WASH Sustainability Index Tool.* **2013**.

(32) Senge, P. The Fifth Discipline: The Art of Practice of the Learning Organization. *Doubleday*, **1990.**

(33) Churchman, C. W. The Systems Approach. Dell Publishing Co., Inc. New York. **1968**.

(34) Bossel, H. (2007). Systems and Models: Complexity, Dynamics, Evolution, Sustainability. *Books on Demand*. Norderstedt, Germany. **2007**.

(35) Bagheri, A.; Hjorth, P. Planning for sustainable development: a paradigm shift towards a process-based approach. *Sustainable Development* **2007** 15 (2), 83-96.

(36) Veeman, T.S.; Politylo, J. The role of institutions and policy in enhancing sustainable development and conserving natural capital. *Environment, Development and Sustainability* **2003** 5 (3) 317-332.

(37) Berke, P.; Conroy M.,M. Are we planning for sustainable development? An evaluation of 30 comprehensive plans. *Journal of the American Planning Association* **2000** 66 (1) 21-33.

(38) United Nations (UN) Secretary-General's High-level Panel on Global Sustainability (2012). Resilient People, Resilient Planet: A future worth choosing. *New York: United Nations*. **2012**.

(39) Wolstenholme, E. System Enquiry: A System Dynamic Approach. *John Wiley & Sons Inc*. **1990**.

(40) Homer, J.,B. Worker burnout: A dynamic model with implications for prevention and control. *Sys. Dyn. Rev*. **1985** 1 (1), 42-62.

(41) Newman, J.; Martin, L. A System Dynamics Approach to Monitoring and Evaluation at the Country Level: An Application to the Evaluation of Malaria-Control Programs in Bolivia. *Operations Evaluation Department, OED Conference*. **2003**.

(42) Ford, A. Modeling the Environment: an introduction to system dynamics models of environmental systems. *Island Press*. **1999**.

(43) Homer, J. A system dynamics model of national cocaine prevalence estimation and trend projection. *Journal of Drug Issues 1993* 23(2) 251-280.

(44) Weaver, E. A. and G. Richardson (2006). Threshold setting and the cycling of a decision threshold. *Sys. Dyn. Rev.* **2006**, 22 (1), 1–26.

(45) Saeed, K. System Dynamics for Discerning Development Problems. Social Science and Policy Studies Department. *Worchester Polytechnic Institute. 2001*.

(46) Bazeley P. Qualitative Data Analysis with NVivo. *Sage Publications Ltd; 2nd Edition*. **2007**.

(47) Godet, M. Introduction to La Prospective. *Futures*. **1986**, 18 (2) 134-157.

(48) Scholz R.W.; Tietje T. Embedded Case Study Methods: Integrating Quantitative and Qualitative Knowledge. *Sage Publications, Inc*. **2002**.

(49) Hallowell, M. R.; Gambatese, J. A. Qualitative research: Application of the Delphi Method to CEM Research. *Journal of Construction Engineering and Management*. **2010**, 136 (1) 99-107.

(50) Linstone, H. A.; Turoff, M. *The* Delphi method: Techniques and applications. *Addison-Wesley, Reading,* Massachusetts. **1975**.

(51) Gratch, H. A. Consensus Measurement in Delphi Studies. *Technology Forecasting and Social Change*. **2012**, 79 (8).

(52) Hsu, C.; Sanford, B. Delphi technique: making sense of consensus. *Practical Assessment, Research & Evaluation*. **2007**, 12(10), 1-8.

(53) Ludwig. B. Predicting the Future: Have you considered the Delphi methodology? *Journal of Extension*. **1997**, 35 (5), 1-4.

(54) Delbecq, A. L.; Van de Ven, A. H.; Gustafson, D. H. (1975). Group techniques for program planning. Glenview, IL: *Scott, Foressman, and Co*. **1975**.

(55) Hwang, K. S. A Comparative Study of Logistics Services in the Container Liner Shipping Market in the UK and South Korea. PhD Thesis. Business School, *University of Plymouth*, **2004**.

(56) Saldanha, J.; & Gray, R. The Potential for British Costal Shipping in Multimodal Chain. *Maritime Management and Policy*. **2002**, 29 (1), 77-92.

(57) Cottam, H.; Roe, M.;Challacombe, J. Outsourcing of Trucking Activates by Relief Organizations. Journal *of Humanitarian Assistance.* **2004**, 1(1).

(58) Islam. D. Dinw Z., O Odie, O. J & Roe J. M. (2006). *Promoting development through multi-modal freight transport in Bangladesh.* Transport Reviews, 26 (5).

(59) Duperrin, J.C.; Godet, M. Méthode de hiérarchisation des éléments d'un système. *Rapport economique du CEA, R*: 45–41, Paris. **1973**.

(60) Torres, N.; Olaya, C. Tackling the Mess: System Conceptualization through Cross-Impact Analysis. *System Dynamics Society Conference Proceedings,* **2010**.

(61) Julius K. A primer for a new cross-impact language—KSIM. In: Harold AL, Murray T The Delphi method: techniques and applications. *Addison-Wesley, Reading*. **2002**.

(62) Monto, M; Ganesh L.,S.; Varghese K. Sustainability and human settlements: fundamental issues, modeling and simulations. *SAGE Publications* Pvt. Ltd, New Delhi. **2005**.

(63) WaterAid Tanzania. Management for Sustainability: Practical Lessons Learned from Three Studies on the Management of Rural Water Supply Schemes. http://www.wateraid.org/~/media/Publications/practical-lessons-rural-water-supply-management.pdf. **2009**.

(64) Carter, R.; Howsam, P. The impact and Sustainability of Community Water Supply and Sanitation Programmes in Developing Countries. J. CIWEM, 13, **1999**.

(65) Montgomery, M.; Bartram, J.; Elimelech, M. Increasing Functional Sustainability of Water and Sanitation Supplies in Rural Sub-Saharan Africa. *Environmental Engineering Science.* **2009**, 26 (5)

(66) Hopkins, O.; Lauria, D.; Kolb, A. Demand-Based Planning of Rural Water Systems in Developing Countries. *Journal of Water Resources Planning and Management*. **2004**, 130 44-52.

(67) Kleemeier, E. The Impact of Participation on Sustainability: An Analysis of the Malawi Rural Piped Scheme Program. *World Development*. **2000**, 28 (5) 929-944.

(68) Choguill, C. Ten Steps to Sustainable Infrastructure. *Habitat International*. **1996**, 20 (3) 389-404.

(69) Kaliba, A. Participatory Evaluation of Community Based Water and Sanitation Programs: The Case of Central Tanzania. Doctoral Dissertation, *Kansas State University*. Manhattan, Kansas. **2002**.

(70) Prokopy, L. The Relationship between Participation and Project Outcomes: Evidence from Rural Water Supply Projects in India. World Development. **2005**, 33 (11) 1801-1819.

(71) Schweitzer, R.; Mihelcic, J. Assessing sustainability of community management of rural wter systems in the developing world. *Journal of Water, Sanitation and Hygiene,* **2012**, 2 (1) 20-30.

(72) Jimenez, A.; Perez-Foguet. Challenges for Water Governance in Rural Water: Lessons Learned from Tanzania. *Water Resources Development.* **2010**, 26(2) 235-248.

(73) Shaw, D. An Assessment of Rural Water Supply Sustainability in Monze District, Zambia. Doctoral Dissertation to *University of Bristol*. Graduate School of Engineering, **2012**.

(74) Foster, T. (2013). Predictors of Sustainability of Community-Managed Handpumps in Sub-Saharan Africa: Evidence from Liberia, Sierra Leone, and Uganda. *Environmental Science & Technology*. **2013**, 47 (21) 12037-12046.

(75) Davis, S. Six Factors for Improving Rural Water Services in Central America. *Global Water Initiative*. **2014**.

(76) Alarcon, L.F.; Ashley, D.B. Project Management Decision Making Using Cross-Impact Analysis. *International Journal of Project Management.* **1998**, 16 (3) 145-152.