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

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

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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 communities¹. 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 construction². 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 time³⁻⁵. 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 project⁶⁻⁹. 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

59 studies investigating the causes of water system failure. For instance, literature has shown
60 communities often lack the necessary capacity to maintain their water system¹², with wells
61 breaking down frequently due to poor maintenance or insufficient water supplies caused by
62 seasonal fluctuations in water levels¹³. In addition, water systems often fail to respond to local
63 needs, desires, and demands, leading to eventual abandonment of the water system^{14,15}. And,
64 finally, a lack of harmonious coordination and alignment between donors, non-governmental
65 organizations, and key stakeholders, coupled with an inefficient use of resources, often stifles
66 effective capacity building of the community, government, and local institutions¹⁶⁻²⁰. These
67 examples, and many others, provide evidence of the complex interaction of technical, political,
68 social, financial, institutional, and environmental influences that can lead to water system failure.

69 In light of these failures, the international water development sector has created
70 evaluation frameworks which use factors and indicators to assess sustainability of existing and
71 future water projects and programs. Indicators have been used to understand and measure levels
72 of community participation^{21,22}, the feasibility of financial management schemes²³, user demand
73 and willingness to pay^{23,24}, supply chain management^{25,26}, and environmental resource
74 management²⁷⁻²⁸, and to evaluate water service sustainability²⁹⁻³¹. These studies have identified
75 the factors that can affect long-term functionality of rural water services through static indicators.
76 However, while these studies have made significant intellectual contributions, evaluating the
77 interaction of factors in this static way may lead to a limited understanding of sustainability by
78 not fully considering their dynamic interaction^{3,5,16}. Thus, the aim of this study was to
79 investigate a methodology to extend existing knowledge on sustainable rural water service
80 provision by considering the dynamic interaction of factors in the form of feedback mechanisms.
81 By including these dynamic and systemic interactions, this study aims to provide motivation for

82 future research focused on finding solutions and remedies to rural water issues that are systemic
83 in nature.

84 **Sustainability.** To improve knowledge on sustainability of rural water infrastructure in
85 developing countries, we must first clarify our definition of “sustainability”. To adequately plan
86 for and maintain rural water systems that are sustainable, the dynamic complexities between
87 factors that often cause project failure must be considered. In this case the term “dynamic
88 complexity”, as defined by Peter Senge³², is used to describe situations where “cause and effect
89 are subtle, and where the effect over time of a particular intervention strategy is not obvious”.
90 Certainly, in the context of planning rural water projects or programs, the cause and effects of
91 failure are often complexly intertwined and not obvious”. Thus, sustainability is best elucidated
92 in processed-based terms³³⁻³⁸. This explicitly requires the holistic systems-based integration of
93 social, political, technical and environmental influences that are present in rural water system
94 operation and maintenance, to create effective and adaptable policy and management systems¹⁶.
95 Thus, in the context of providing sustainable rural water services, planning largely becomes a
96 process of interpreting, and adapting to the dynamic interaction of factors that influence long-
97 term functionality.

98 **System Dynamics Modeling.** System dynamics modeling is a process used to describe and
99 simulate dynamically complex issues through the structural identification of closed-system
100 feedback mechanisms that drive system behavior⁷⁻¹⁰. Following its inception in 1961 by
101 Michigan Institute of Technology (MIT) professor, Jay Forrester, system dynamic modeling has
102 been used for a wide range of applications. Specifically, there is a long tradition of using system
103 dynamics to study public management issues¹⁰ including public health^{40,41}, energy and the

127 structure hypothesized to drive the dynamic behavior of the system. In this case, dynamic
128 behavior manifests in the emergence of feedback mechanisms often called “feedback loops”,
129 where a feedback loop is a causal chain of two or more factors that reconnects to influence each
130 factor in succession over time¹⁰. Since the aim of this study was to hypothesize the feedback
131 mechanisms that affect long-term functionality of rural water services, this research focused
132 solely on the qualitative system dynamic modeling process.

133 The creation of dynamic theory in the form of a CLD followed a three-phase process.
134 Phase 1 entailed identifying and defining the factors that were used to describe the dynamic
135 behavior of the system, by conducting a systematic literature review. Phase 2 involved making
136 distinctions regarding the “polarity of influence” and “strength” between each factor from a
137 panel of water sector experts using a *polarity analysis* and *cross impact analysis (CIA)*,
138 respectively. Lastly, Phase 3 identified and ranked dominant feedback mechanisms using the
139 Phase 2 results from the CIA. Due to the multi-method approach employed for this research, we
140 present the method, followed immediately by the results, for each phase.

141 **Phase 1: Factor Identification.** To identify the factors used in the CLD we performed a
142 content analysis of scholarly journals and journals published informally within the water sector
143 using different combinations of the keywords “rural water”, “developing countries”,
144 “sustainability”, “factors” and “indicators”. Scholarly articles were searched within the “Web of
145 Knowledge” and “Engineering Village”. The process began by reading the abstract of each
146 article found in the keyword search to ensure the research premise was related to rural water
147 project sustainability in developing countries. Articles that did not meet this requirement were
148 excluded. We coded and aggregated recurring references within the literature to factors that
149 affected the sustained functionality of a rural water system in a developing country context. The

150 coding process was performed within the qualitative data analysis software, QSR NVivo, chosen
151 for its ability to easily allow researchers to code and manage qualitative data⁴⁶. Finally, these
152 coded factors were grouped within affiliated categories called “sustainability factors” to ensure
153 the number of factors included in the CLD were of a manageable size while covering the
154 spectrum of key themes related to rural water service sustainability^{47,48}.

155 The initial keyword search yielded 472 articles within scholarly journals and 176
156 informal articles found within the water sector. From these, 97 were chosen for their explicit
157 identification of factors that influence long-term functionality of rural water services in
158 developing countries. These 97 articles yielded 157 unique references to factors that potentially
159 affect sustainability and functionality of a rural water system. These factors were then
160 aggregated into “sustainability factor” affiliation categories, which included: *Government (Gov)*,
161 *Community (Com)*, *External Support Management (Ext)*, *Financial (Fin)*, *Environment &*
162 *Energy (E&E)*, *Technology Construction & Materials (TCM)*, and *Water System Functionality*
163 *(WSF)*. The factor “Water System Functionality” relates to how the water system is functioning
164 at any particular time, and is not to be confused as the emergent outcome of long-term
165 functionality.

166 Table 1 summarizes these sustainability factors, including a definition, the key sub-
167 factors mentioned in the literature for each sustainability factor, and the number of articles that
168 mentioned each sub-factor. The language used to define each factor was intentionally kept
169 positive per best practices for causal loop diagramming⁸. To this end, a common thread of these
170 definitions was chosen as “the ability”, where this “ability” relates to how the factor either
171 enables or inhibits the objective of long-term water service functionality. Thus, as we progress
172 into the identification of feedback mechanisms, it will be important for the reader to understand

173 that these sustainability factors are thought to have a type of “capacity” or “ability” to, over time,
 174 increase or decrease in a way that influences overall project success (long-term functionality) or
 175 failure.

176 **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 |

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

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

183 *Polarity Analysis.* Using the factors identified in Phase 1, a Delphi panel of water sector
184 experts was assembled in an attempt to reach consensus regarding the polarity of influence and
185 associated model structure between the identified sustainability factors using expert assessments.
186 The Delphi Method is a research technique to facilitate consensus within a group of experts
187 regarding underlying relationships among causal factors^{11,49-51}. This is typically done through a
188 multi-round survey whereby panelists are presented in each subsequent round with the aggregate
189 group responses from the previous round in an attempt to facilitate consensus on a series of
190 themes. Polarity of influence relates to the dynamic nature of pair-wise influence between
191 factors, where this influence can either be positive (an increase in one factor leads to an increase
192 in the other) or negative (an increase in one factor leads to a decrease in the other). Identifying
193 the pair-wise polarity of influence between each of the factors provides the necessary building
194 blocks for causal loop diagramming and the identification of feedback mechanisms (Phase 3).

195 A thoughtful selection of experts for the Delphi panel was considered critical to the
196 quality of the study, as many researchers reference non-uniformity between panelist expertise as
197 a major weakness of the methodology⁵². Thus, a 6-point criterion was used to select panelists,
198 shown in Table 2, per recommendation of Hallowell et al. (2010)⁴⁹. These criteria were created
199 based upon the desire for panelist expertise and experience in rural water service sustainability in
200 developing countries. To ensure a sufficient amount of panelists remained through the 2 rounds
201 of this Delphi, we over sampled and chose 23 panelists using the criteria shown in Table 2^{52,53}.
202 Of these 23 panelists, 9 were consultants or advisors, 12 were directors, and 2 were academics,
203 all focusing on sustainability of water systems in either Africa, Latin America or Asia. Panelists

204 were given two weeks to respond to each round, an amount of time that is typically considered
 205 sufficient to allow panelists flexibility within the context of their schedules, yet short enough to
 206 have the study conducted in a reasonable timeframe⁵⁴.

207 **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 |

208 The Panelists were sent Qualtrics online survey questionnaires that asked them to indicate
 209 the influence of each sustainability factor on the other factors. Consensus between panelists for
 210 each influence was determined using a method known as the “Average Percentage Majority
 211 Opinion” (APMO). This was chosen as the preferred determinant for consensus as it was
 212 predicted that high levels of variability would exist in the overall agreement regarding influences
 213 between factors. APMO is an appropriate metric for general consensus in cases such as this,
 214 where panelist agreement is used as a viable indicator of consensus⁵⁵⁻⁵⁸. Using APMO each
 215 consensus limit between factors (factor A on B, C, D...etc), was considered on a factor-by-factor
 216 basis. APMO had to be 51 percent, or greater, to be used as a limit for consensus, per the
 217 definition of majority⁵¹. The equation for APMO is shown below.

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

219 In Round 1, the experts were acquainted with the objective of the study and given
 220 definitions for each of the factors, as shown in Table 1. Each expert was then asked to indicate

221 the polarity of influence between the sustainability factors. For example, to obtain responses on
222 the polarity between a particular factor—such as Factor A on Factor B—each expert was asked
223 to select an option regarding how Factor A would influence Factor B, either: (+)—an increase in
224 Factor A will cause an increase in Factor B; (0)—there is little or no influence between Factor A
225 and Factor B or; (-)—an increase in Factor A will cause a decrease in Factor B.

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

231 In Round 2, each panelist was asked to again make pair-wise comparisons regarding the
232 influence between the factors that did not reach consensus in Round 1 (29 influences). In this
233 round, however, panelists were presented with the aggregated responses of the other panelists.
234 Per typical Delphi protocol⁵¹, this was to see if a panelist reinterpreted the questions based upon
235 the responses from the other panelists. Round 2 reached consensus on an additional 15 polarities,
236 resulting in a total of 42 influences that reached consensus and 14 that did not. Influences that
237 did not reach consensus were not included in the final causal loop diagram. For the 42 influences
238 that reached consensus, 33 had positive polarity (+: direct relationships), 9 had no influence (0),
239 and 0 had negative polarity (-: indirect relationship). A causal loop diagram (CLD), created using
240 the consensus results on factor influence from Round 1 and 2 of the Delphi, is shown in Figure 1.

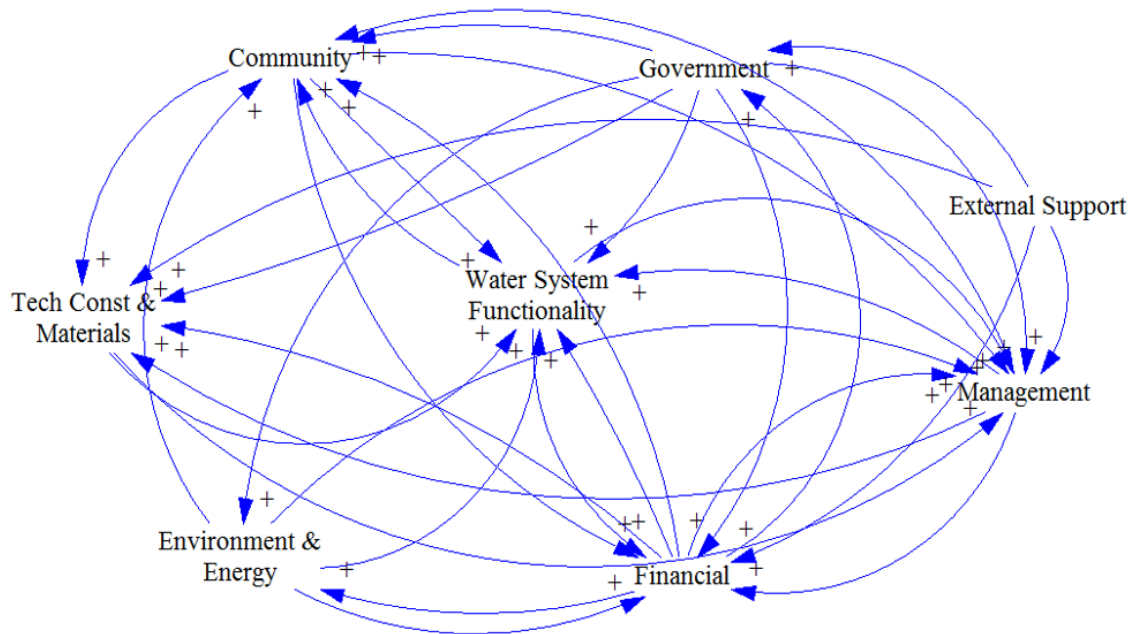


Figure 1. Causal loop diagram from the polarity analysis

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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 factors⁵⁰. 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

256 influences. The statistical mode was chosen as the appropriate measure of centrality due to the
257 categorical nature of the data. Table 3 shows the impact matrix for each causal influence.

258 **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 |

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260 **Phase 3: Feedback Mechanisms.** After polarity and strength between factors were
261 identified from Phase 2, the causal loop diagram (CLD) (Figure 1) was imported into the
262 Ventana Systems Inc.'s VENSIM system dynamic modeling software (www.Vensim.com) to
263 identify feedback loops that influenced water system functionality using the program's "loop"
264 tool. Combining interactions identified in the polarity analysis and CIA, it was possible to
265 identify 101 unique feedback mechanisms that influence the factor Water System Functionality -
266 - in such a way so as to influence long-term water system functionality

267 The question remains, which of the 101 feedback mechanisms most influences long-term
268 water system functionality? To address this question, the study used factor influence ranking
269 with the Cross Impact Analysis (CIA) data to identify dominant feedback mechanisms⁵⁹. Using
270 the CIA impact matrix created in Phase 2, loop strength was calculated by summing pair-wise
271 influence scores for each factor within each causal loop. Loop scores were normalized based on
272 the number of factors within the loop to enable comparison. For example, WSF-Com-Fin-Man
273 from the impact matrix was calculated as $(3 + 2 + 3 + 3)/4 = 2.75$. The feedback loops with
274 normalized scores of 2.4 and above are shown in Table 4.

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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 |

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Results and Discussion

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Several compelling findings may be inferred from the results of this study. From the

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polarity analysis, water experts in Rounds 1 and 2 of the Delphi indicated that all existing

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influences between factors were positive (+). This means the resulting feedback loops are

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all “reinforcing” and would likely lead to a system behavior that is either one

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of “growth” (increasing), “decay” (decreasing), or a combination of both, depending on

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the dominance of the loops over time. In the context of a rural water system, a reinforcing

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feedback loop could imply water services that are increasing in functionality, or decreasing

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functionality over time. An interesting example in the case of the former, a study by WaterAid

287 Tanzania in 2009 observed a dramatic decrease in water system functionality over 2 to 7 years
288 that seems to match this trend in functionality⁶³. These examples support the inferred dynamic
289 nature found using the CLD (Figure 1).

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

301 These results are well-aligned with water sector literature, which suggest community
302 involvement and effective financial and management schemes greatly influence the long-term
303 functionality of rural water infrastructure in developing countries. Specifically, the literature
304 mentions that a community’s capacity to effectively engage with a rural water system is affected
305 largely by the community’s perceived need for a potable water system (thus creating a demand)
306 and the community’s involvement in the decision and selection process of the technological
307 solution^{15,64-71}. Additionally, there are many proponents for a framework that involves the
308 community in managing the operation and maintenance of the water system^{5,15,65,72}. Conversely,
309 many experts in the literature believe communities inherently lack the necessary capacity to

310 manage a water project and suggest a model that heavily involves external institutional support
311 by the government and organizations to provide guidance, legal frameworks and regulations for
312 the proper operation and maintenance of a rural water system^{16,73}. Existing research also
313 critically analyze existing management approaches as requiring a financial plan for recurrent cost
314 recovery, typically in the form of monthly household tariffs, to fund the operation, maintenance
315 and eventual overhaul of the water system^{24,67,74}. Additionally, a recent study by Davis (2014)
316 explicitly tied together the affect Water System– Functionality–Community–Financial–
317 Management has on rural water system sustainability in Central America⁷⁵. This past work offers
318 great support for the factors, and the nature of their causal interaction, identified in the dominant
319 feedback mechanism found in this study.

320 However, the top rank loop (Water System– Functionality–Community–Financial–
321 Management) is only one of 31 other top-five ranked feedback mechanisms found in this study,
322 many of which also included the factors: Government and TCM (see Table 4). Certainly an
323 argument can be made that any of these other feedback mechanisms could be equally, if not
324 more important. For example, in a particular context the loop WSF-Fin-Gov-Man, could
325 conceivably be more dominant in a context where the management (operation and maintenance)
326 was instead the responsibility of the local government. This provides a intriguing case for
327 additional research efforts that elaborate on feedback mechanisms within different contexts (e.g.
328 country, technology, management scheme). With the insight gained by these data, it may then be
329 possible to develop quantitative models to simulate, explore, and learn more about the interaction
330 of key factors that influence long-term functionality of future rural water projects.

331 Ultimately, there are intrinsic benefits to engaging in modeling of this type as a way to
332 articulate the structuring of a problem⁷⁶. As Godet⁴⁷ mentions a systems modeling process can

333 serve to foster “adaptive learning [as a way] to stimulate collective strategic planning and
334 communications, to improve internal flexibility when confronting environmental uncertainty and
335 to better be prepared for possible disruptions and adapt to choice of actions to the future context
336 to which the consequences of the actions would relate” (pp. 139). Similarly, the process of
337 defining and describing a dynamic feedback mechanism offers a powerful means to hypothesize
338 how a particular phenomenon unfolds over time⁷. To that end, this research presents an initial
339 framework for how future research of this type may be conducted using expert (or stakeholder)
340 opinion for the production of knowledge and understanding on the feedback mechanisms that
341 influence long-term functionality of rural water infrastructure. This could allow for an extension
342 of sustainability frameworks for rural water project assessment, which are currently static, into a
343 dynamic systems-based paradigm of decision making, using longitudinal case data in varying
344 contexts. We believe that continuing to improve understanding on the dynamic interaction of
345 factors that cause premature failure will help enable rural water projects and programs to provide
346 communities with permanent access water services.

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

354 The Delphi expert panel also had potential for errors due to the limitations inherent in the
355 methodology itself. Responses from panelists may have been skewed due to the particular

356 interpretation of the question context, given the inability for panelists to resolve confusion in a
357 group setting. There were many instances where panelists conveyed the difficulty in
358 generalizing water system functionality from a “high level”, and often desired firmer contextual
359 grounding from which to indicate the influences between factors. Additionally, an unavoidable
360 limitation of this study was the subjectivity in assumptions taken by both the authors as well as
361 the expert panelists regarding factor identification, interaction and feedback loop dominance.
362 Thus, developing a way to better navigate this subjectivity, while producing meaningful results,
363 will be paramount for future studies.

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