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Article

Understanding Rural Water Services as a Complex System: An Assessment of Key Factors as Potential Leverage Points for Improved Service Sustainability

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Abstract: Rural water supply services worldwide consistently fail to deliver full public health impacts as intended due to a low service sustainability. This failure is increasingly attributed to weak local systems composed of social, financial and environmental factors. Current approaches in the water, sanitation and hygiene (WASH) sector for understanding and improving these systems typically focus on the strength and capacity of these factors, but not the interactions between them. We contend that these approaches overlook the inherent complexity and context-specific nature of each local system. To assess this complexity, we conducted four participatory factor mapping workshops with local stakeholders across multiple rural water contexts to identify the factors and interactions that support service sustainability. We then evaluate the potential for factors to act as strategic leverage points based on influence, dependence and feedback metrics that arise from their interactions with other factors. We find that while participants across the contexts tend to identify a common set of factors, the interactions amongst those factors and their individual ability to influence service sustainability varies considerably across contexts. These findings suggest that a more intentional focus on factor interactions in WASH systems could lead to more effective strategies for improving service sustainability.

Keywords: Rural water service delivery; systems thinking; complex systems; causal loop diagramming; WASH

1. Introduction

Despite a highly uniform and proven set of technologies and approaches in the WASH sector for delivering services [1], more than a quarter of existing rural water infrastructure worldwide consistently fails to function as intended [2,3]. In sub-Saharan African countries, up to 70% of rural water schemes are estimated to be nonfunctional or intermittently functional at any given time [4]. In response, the rural water supply sector has identified the improvement of service sustainability as a key challenge for installed infrastructure to deliver its intended public health impacts [5,6].

To address this issue, the water, sanitation and hygiene (WASH) sector has begun moving beyond a conventional paradigm which emphasized the installation of new infrastructure, and towards an approach that embraces a ‘systems’ perspective of services [7–9]. This systems approach contends that the sustainability of WASH services is driven by the collective impact of many technical and

nontechnical factors [10,11]. By taking a more holistic view, this approach suggests that issues of low service sustainability are not due to the deficiency of any individual factor (e.g., hardware), but rather the collective weak effect of many factors (e.g., social, environmental, financial). Thus, improving service sustainability cannot be achieved by strengthening individual factors, but requires a broader perspective of strengthening the whole system of factors [12].

To evaluate how these factors may be driving service delivery outcomes, the sector has developed wide range of frameworks to measure the individual and collective capacity of factors to sustain services [13]. An implicit underlying assumption of these frameworks is that when a majority of the factors have a high individual capacity, there is a correspondingly high likelihood of services being more sustainable [14]. Conversely, if most factors had a low capacity this would indicate a lower likelihood of service sustainability. However, this approach overlooks a fundamental concept of systems thinking; the outcome of the system (i.e., service sustainability) is not simply an aggregation of the strength of its individual factors, but the collective effect of the *interactions* between those factors [15–17]. An enhanced understanding of how these interactions affect service sustainability is arguably as important, if not more so, than an assessment of the factors themselves.

The critical role of factor interactions is receiving more attention within an emerging theme in sector literature that increasingly refers to the combination of factors that support WASH services as a “complex” system [18–22]. Complex systems theory describes such systems as ones in which relationships between factors result in dynamic, nonlinear and unpredictable behaviors that are specific to each system within a given geographic or environmental context [17,23]. The interaction between these factors form ‘feedback loops’, which represent chains of cause and effect relationships that propagate information and resources through the system, driving the systems’ outcome behavior [24]. Because of the highly connected nature of complex systems, changes in the state of any individual factor or interaction can lead to larger changes in the system overall through their connections to other factors and interactions [25], a phenomenon commonly known as the “butterfly effect” [26]. Key places within the system where small changes can lead to disproportionately larger changes in the system are commonly referred to as “leverage points”. Identifying where these leverage points are located in a system and understanding how they can be adjusted to lead to more favorable outcomes is an essential element of a effectively strengthening complex systems [27].

While literature in the WASH sector increasingly invokes complex systems rhetoric [18,28,29], many of the existing tools available to practitioners for assessing WASH systems often do not analyze interactions between factors. Previous work that has investigated interactions between factors in WASH systems includes the use of Bayesian networks [30,31], system dynamics [32], concept models [33], and agent-based modeling [34]. However, these analyses have either focused on the interaction of factors within a particular context—usually geopolitical—or sought to develop generalizable findings which could be applicable across multiple contexts. Both approaches appear to underappreciate the uniqueness of complex systems as a response to their distinct local environment and historical development [35]. Additionally, while a wide range of technical, environmental and social factors have been hypothesized to strongly affect service sustainability [36–41], there appears to be little consensus in the literature of which specific factors, individually or collectively, are most critical for sustaining WASH services, or if the importance of these factors varies across context.

Furthermore, many studies of WASH systems seem to rely heavily on the perspectives of external technical experts and seldom give equal weight to the perspectives of local stakeholders. This approach overlooks a critical viewpoint as many of these stakeholders (e.g., operators, regulators, NGOs) are responsible for a majority of the day-to-day decision-making that most acutely influences service sustainability [42]. Indeed, research shows that the degree to which decision makers’ perspectives are aligned with other actors who work within the same systems has a significant effect on their collective ability to strengthen those systems [43–45]. The perspectives of local stakeholders are particularly important for understanding complex systems with factors and interactions for which objective quantitative data is not available or possible to collect (e.g., factors of community participation,

political will, cultural norms). In these circumstances, the experiences of those who interact with the system most may serve as the only available database of the state of key factors and the cause and effect relationships between them [46,47]. Thus, to develop a more informed understanding of how both quantitative and qualitative factors in complex systems interact with one another, it is critical to include the perspectives of those who have the most intimate contextual knowledge of the structure and dynamics of those systems [48].

1.1. WASH as a Complex System

We propose that a more nuanced understanding of how WASH services operate as a complex system, including an explicit analysis of factor interactions, is necessary to systematically identify leverage points that can lead to the design of more effective strategies for strengthening systems that support service sustainability. We define a local system for rural water services as consisting of all the factors and their connections that are thought to have a direct or indirect influence on service sustainability. Within these systems, factors represent any tangible or abstract entity that can affect another factor in the system (e.g., finances, water resources, policies) and/or an outcome of that system (e.g., coverage, functionality, sustainability). The combination of factors and their interactions with one another within a given context can be understood to be the system's underlying structure, from which system behavior arises.

Drawing on theory from the fields of system dynamics, structural analysis and scenario planning [49–51], we evaluate the potential of a variety of factors to act as leverage points within WASH systems. We assess the leverage point potential of each factor based upon a combination of a factor's influence (how it affects other factors), dependence (how it is affected by other factors) and its presence in prominent feedback loops (how it contributes to dynamic outcomes). A factor with a high potential to act as an effective leverage point would ideally have a high influence on the system, low dependence on other factors, and be common within dominant feedback loops. To understand how these leverage points may vary across contexts, we will examine factor interaction in different geographic contexts with similar rural water service delivery characteristics.

Thus, our study seeks to address three key questions;

1. What factors do local stakeholders identify as critical to sustaining WASH services?
2. How do these factors interact with one another to affect WASH service sustainability?
3. What aspects of these factors and their interactions are common across contexts and which are context-specific?

1.2. Context

As rural water services have been a main focal point of systems thinking in the WASH sector [52,53] we have chosen to examine the factors and interactions necessary for sustaining these services, specifically in rural sub-Saharan African communities (SSA). For this purpose, we chose four geographic case study contexts in Uganda and Ethiopia with rural water service delivery conditions that are relatively comparable to one another and also broadly representative of rural water services in SSA (SS1). Each context represents a geopolitical boundary of a district or woreda, an administrative level where key policy decisions are most commonly made around infrastructure service provision in decentralized systems of governance.

Each of the four contexts contain rural water service delivery schemes based around a combination of community or local management with varying levels of government support as well as some private sector services (Table S1). These contexts also exhibit water access and functionality rates typical of rural water service delivery in SSA countries, where an estimated 58% of the population has access to basic water services [54], with average functionality rates of 78% [5].

2. Methods

To evaluate the leverage point potential of factors to leverage systems for improved service sustainability, we conducted group model building (GMB) workshops in each of the four contexts with local stakeholders to identify key factors and their influence on one another. We then analyzed factor influence, dependence and feedback loops based solely on interactions identified by the participants in cross-impact matrices produced in each workshop. Having quantified these three leverage point attributes for each factor within each context, we then compared findings across contexts based on common factors identified in two or more workshops.

Across the four contexts, we brought together (62) local stakeholders representing key decision makers including local and regional government officials and civil servants (51) and nongovernmental organizations (11). The average workshop group size was 14 participants. Representatives of these organizations were selected and convened by local partner organizations with long term presence in each context to provide a diverse set of perspectives on rural water service delivery. Workshops lasted from one to six hours with an average duration of three and a half hours. A study protocol for the workshops and data collection was reviewed and approved by the University of Colorado's Institutional Review Board (IRB # 17-0292) and all participants gave their informed consent for inclusion before they participated in the workshops.

Building upon participatory system dynamic methods [55–58], this work used a 'Factor Mapping' workshop format to elicit knowledge about factor interaction and dynamics as developed by Walters et al. [59–62]. The GMB approach provided a structured process for engaging knowledgeable stakeholders in discussions around complex problems [46,63,64]. Each factor mapping workshop consisted of a facilitated group discussion where participants are asked to identify the factors that they believe are most influential to sustaining rural water services. The group is then asked to describe the relative strength and polarity, or directionality, of the direct influence that each factor exerts on the others. Here *direct* influence refers to the immediate effect that a factor has on another (i.e., $A \rightarrow C$), as opposed to an *indirect* influence that creates an effect through an intermediary factor (i.e., $A \rightarrow B \rightarrow C$). The strength of a factor-on-factor influence, and the polarity of that influence are independent attributes of the relationship where one does not affect or preclude the other.

To map factor interactions, the workshop used a "Cross-Impact Matrix" with row and column headings representing each factor, and an 'outcome factor' representing water service sustainability (Table 1). Each cell in the matrix represents the influence of the factor in the corresponding row on the factor in the corresponding column. The cells across the diagonal in the matrix are blank because factors are not considered to influence themselves. To populate the matrix participants are asked to rate the strength of each direct influence on a scale of 0–3 where; 0—no connection, 1—weak influence, 2—moderate influence, 3—strong influence. For example, in the Kamuli context (Table 1)—which we will use for demonstrative purposes throughout—*Water User Committees* were identified to have a moderate (2) influence on *Mechanics* (row 1, column 2) (Individual factors are represented as a proper noun (capitalized) in italics).

Each cell contains the strength and polarity of influence from the factor in the row onto the factor in the respective column. Strength is represented as 0—no connection, 1—weak influence, 2—moderate influence, 3—strong influence; polarity is represented as positive (+/no sign) or inverse (–).

Participants are also asked to identify the polarity of each influence as either positive (+); as the state of the cause factor improves so does the affect factor, or as negative or, inverse (–); as the state of cause factor improves the state of the affect factor diminishes, or visa-versa. For example, in the Kamuli context, participants noted that there was a weak inverse influence (–1) of *Service Sustainability* on *Monitoring* which was based on the participants' belief that if water services were consistently and reliable functional, then there would be less of an incentive to monitor them. Completion of the matrix was based on a consensus of simple majority of the participants in the workshop (i.e., greater than 50% agreement).

Table 1. Example cross-impact matrix from Kamuli factor mapping workshop representing the interaction of factors.

	Water User Committee	Mechanics	User Fees	Political Support	Water Source By-Laws	Monitoring	Spare Parts	Water Users	Service Sustainability
Water User Committee		2	3	1	3	1	3	3	3
Mechanics	1		1	0	1	2	3	1	3
Water User Fees	1	3		1	1	2	3	3	3
Political Support	3	0	1		3	2	1	2	1
Water Source By-laws	3	1	3	1		1	1	3	3
Monitoring	2	3	1	1	1		2	1	1
Spare Parts	1	2	3	1	1	2		1	3
Water Users	3	2	3	1	3	3	3		3
Service Sustainability	3	3	3	1	3	-1	-3	3	

By using this simple rating scale for factor strength and a dichotomous descriptor for polarity, this process breaks down the complexity of modeling a complex system into individual interactions. Instead of mapping all the elements of the system at once, the process allows participants to discuss factor-on-factor influences one at a time and assign each relationship a relative quantitative rating. This process was used intentionally to overcome participants' innate 'bounded rationality'; the inability to conceive of a whole system based on only the parts one knows [16] and the cognitive human limit of analyzing multiple complex interactions simultaneously [65,66].

Following each workshop, the values in the tables are analyzed for three metrics used to assess leverage point potential; *influence*, *dependence* and *feedback*. Factor influence and dependence are calculated using an established and simplified method referred to as MICMAC (Matrix Of Cross Impact Multiplications Applied To Classification) [49,50,67]. In this process, the influence and dependence are calculated by summing the values in each row and column, respectively. The factors are then ranked by these two metrics to evaluate the relative strength each factor has in influencing other factors, and the collective dependence that each factor experiences from the other factors in the matrix. The MICMAC method has previously been used widely to assess multivariate complex systems, including the interdependencies of critical infrastructure [68], identifying strategic variables in urban planning [69], and managing growth of complex energy sectors [70,71].

In addition to influence and dependence, the values in the cross-impact matrix can be used to identify dominant feedback loops that either promote or inhibit desirable outcomes of the system [17,72]. Feedback loop analysis is conducted in a three-step process. First, a causal loop diagram (CLD) is developed that graphically represents all factor influences in the matrix by drawing a line between factors for each nonzero influence [73] (Figure 1). Next, the CLD is analyzed using Vensim System Dynamics software to identify all possible unique feedback loops that begin and end at the factor of interest (e.g., Service Sustainability) [74].

Using the polarities identified by the participants, feedback loops are then classified as either reinforcing (compounding) or balancing (stabilizing). The reinforcing or balancing nature of the loops is determined by the balance of positive and inverse relationships in the sequence of each loop. If the total number of inverse relationships in the loop is an even number, the loop will produce a reinforcing behavior, whereas an odd number of inverse relationships indicates a balancing behavior [75]. For example, in Kamuli the feedback loop of *Service Sustainability* → (-) *Monitoring* → (+) *Service Sustainability* suggests that as service sustainability improves, monitoring may decrease (as explained by workshop participants). However, as *Service Sustainability* decreases, this would (as

participants described the relationship) have an inverse effect that could lead to an improvement in *Monitoring*, further improving *Services*, thus generating a balancing behavior in the system.

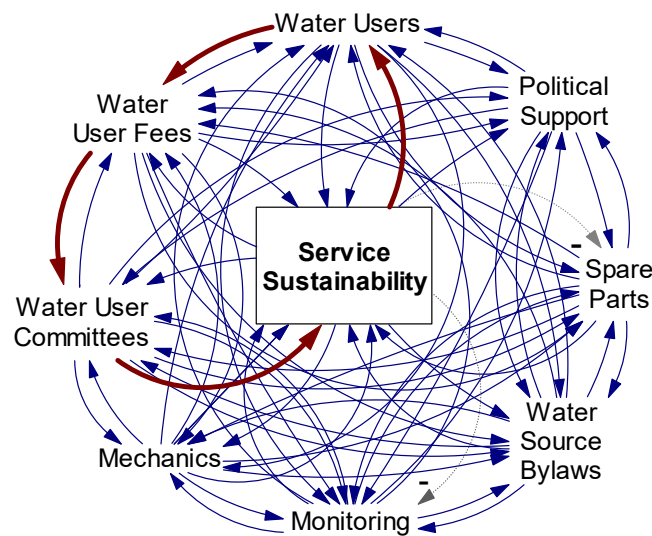


Figure 1. Causal loop diagram (CLD) representing all nonzero interactions identified in the cross-impact matrix of Kamuli workshop. Head of arrow indicates the direction of the influence. Inverse relationships designated with a dotted line and (-) sign next to arrowhead. Feedback loop highlighted for illustrative purposes: Service sustainability → water users → water user fees → water user committees → service sustainability. Dotted lines represent inverse factor influence.

Finally, to be able to infer which of the feedback loops are most likely to drive system behavior, each loop is quantified by averaging the strength of all the influences between each factor in the loop [59] (Equation (1)). This creates a ‘normalized score’ for each feedback loop. For example, the feedback loop highlighted in Table 1, would yield;

Service Sustainability → (3) Water Users → (3) Water User Fees → (1) Water User Committees → (3) Service Sustainability

$$\frac{\sum_{i=1}^n (\text{Cause Factor} \rightarrow \text{Effect Factor})_i}{n} = \frac{(3 + 3 + 1 + 3)}{4} = 2.5 \quad (1)$$

Note that polarities are not considered in this equation as the +/- signs identified in workshop do not represent positive or negative values relative to a zero value. The process of quantifying relative loop strength into a normalized score does not diminish the complexity of the analysis, as the unique combinations of factors and causal links within each loop are the direct result of the complex system analytics performed by the Vensim system dynamics software. Thus, using this method, feedback loops can be quantified and ranked by their overall strength relative to other feedback loops from the same CLD.

While the use of values of 1, 2 & 3 for influence strength are a useful scale for identifying weak, moderate and strong influences, using these values in the quantification process of feedback loops would result in multiple loops having the same normalized score due to a limited number of combinations of these values. To circumvent this limitation, we employ the use of indirect influence matrices that can be calculated from the original cross-impact matrix using the MICMAC method. The indirect influence matrix (Table S2) is generated by multiplying the cross-impact matrix by itself in iterations. This matrix multiplication is repeated until the matrix achieves ‘stability’. This is determined by sorting each factor by its *direct classification*; its relative ranking of the number of potential feedback loops produced by the factor and the number of other loops in which the factor is present, proxy indicators of influence and dependence, respectively [49]. After each iteration of the

matrix multiplication, the factors are re-ranked by this direct classification. When the classification ranking of factors does not change with subsequent iterations, the matrix is said to achieve stability, thus producing a matrix of indirect influences (Table S2) [50]. On average, this process requires three to five iterations to reach stability for matrices of 10–15 factors. By substituting the assigned factor influence ratings (1–3) with values from the indirect influence matrix, the normalized scores of feedback loop rankings will produce a larger range of values, allowing for a more detailed analysis for identifying feedback loops that are most likely to drive system outcomes. Indirect matrices can also be used to assess indirect factor influence and dependence for comparison to rankings from the direct cross-impact matrix.

Further details on the factor mapping GMB process, including additional information regarding the workshop facilitation, data elicitation and analysis are presented in our summary reports of work conducted with the Sustainable WASH Systems Learning Partnership [76,77].

3. Results

Across the four factor mapping workshops, participants collectively identified 48 factors (average 12 per group) thought to be influential to sustaining rural water services. Of these factors, 37 (average 10 per group) were determined by the participants to be priority factors and were subsequently included in the respective cross-impact matrices. This resulted in the assessment of 380 unique factor-on-factor influences across the four workshops (Table S2). Overall, participants in the four groups identified similar factors, but each group used slightly different terms and definitions to delineate these factors (Table S3). To compare the leverage point criteria of these factors across contexts (influence, dependence, feedback loops), the factors were affinity grouped into 13 representative common factors. This list of common factors (Table 2) shows that the four groups are relatively aligned with one another on the factors needed to sustain rural water services. These factors also closely mirror the social, technical, environmental and financial factors commonly found in sustainability frameworks in the sector [13].

Table 2. Common factors included in the cross-impact matrices of two or more groups.

Common Factors	Kabarole	Kamuli	Mille	South Ari
Community	X	X		X
Coordination	X		X	X
Financing	X		X	X
Hardware	X	X	X	
Local Capacity	X		X	X
Mechanics		X	X	
Monitoring		X		X
Operation & Maintenance (O&M)	X			X
Planning		X	X	X
Politics	X	X		
Regulations		X		X
Users		X	X	X
Water Resource Management (WRM)	X		X	X

See Table S3 for unique factor names and definitions as described by workshop participants.

3.1. Influence and Dependence

Using the influence scores assigned in the cross-impact matrix from each workshop, a normalized rank score of influence and dependence were developed for each factor on a 0–1 scale; 0 being the bottom rank and 1 being the top rank. The normalized rankings for each factor were then combined across all workshops to determine the low, median and high rank for common factors across contexts (Figure 2) (Figure S1). This comparative ranking provides insights into how each common factor's influence and dependence rankings compare across context.

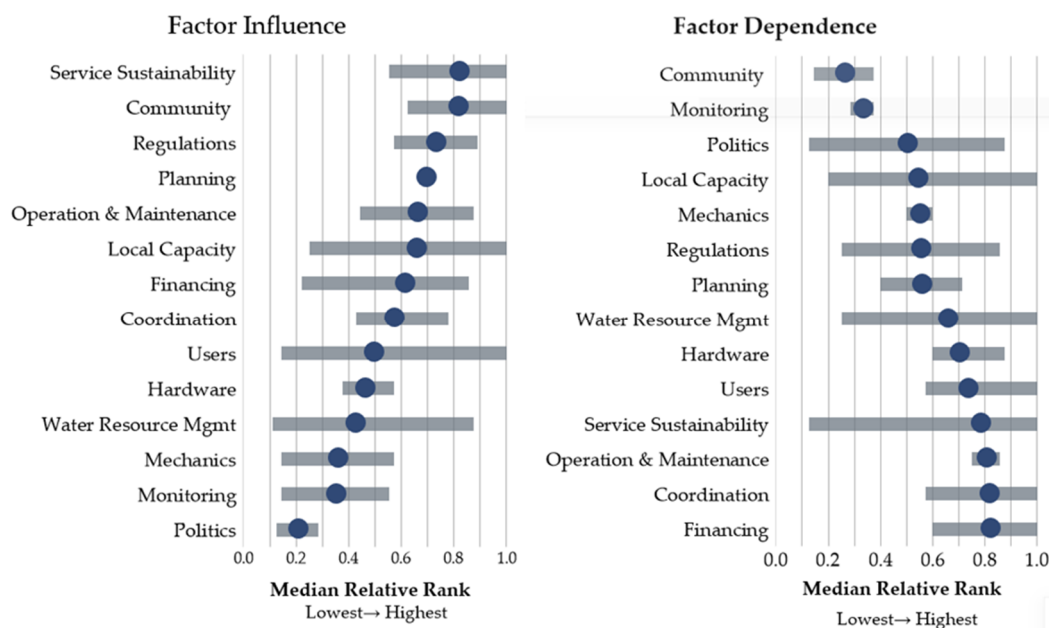


Figure 2. Median relative ranks of Influence and Dependence for common factors across contexts (dot) overlaid on range of high and low scores from all contexts (grey bar).

3.2. Factor Influence

Scores for factor influence—the degree to which a factor effects all the other factors—shows that the outcome factor *Water Service Sustainability* and the *Community* factor shared the overall highest influence of all factors. This suggests that the existing state of services affects the factors that contribute to the sustainability of that service, illustrating a feedback behavior. Participants described positive feedback effects of increasingly reliable services as promoting community involvement in managing the source and improving users’ willingness to pay for services. Participants also noted inverse effects of improved service sustainability as leading to less financial investment (Kabarole), less supervision and monitoring (Kamuli), and overall less demand for services (Mille). One participant described the effect of Water Service Sustainability on Financing as, “If the existing sources are more reliable, government and NGO funding will be reallocated to other sources”.

The high influence ranking of the service itself indicates the importance of understanding the feedback of the outcome factor on the rest of the system. However, overall the cross-context influence comparison shows a wide range of rankings across the four locations for nearly all factors with the exception of *Planning* (ranked fourth) and *Politics* (ranked the lowest). The role of *Users* in particular was shown to be both the most influential factor in Kamuli and one of the least influential factors in Mille, South Ari.

3.3. Factor Dependence

Rankings for factor dependence—the degree to which a factor is affected by all other factors—show similar findings to the influence analysis with a wide range of rankings across the four contexts. The three factors with the highest dependence scores—*Financing*, *Coordination*, and *O&M*—all relate to factors that require many inputs for them to operate effectively. Of these factors, the operation and maintenance process likely relies on the widest array of factors [78], which may explain the smaller range of dependence rankings for the *O&M* factor across contexts.

The least dependent, or most independent, factors of *Community* and *Monitoring* had the least variation across the four contexts. The high independence of these factors suggest that they require the least amount of inputs from other factors to change or improve their condition. For example, in Kabarole, the group noted that factors such as *Financing*, *Hardware* and *Local Government Capacity* had

very moderate effects on the level of ownership that users exert over their water sources, indicating that *Community* was a more independent factor from the others. Similarly, in Kamuli, participants noted that the only strong influence on *Monitoring* comes from *Water Users* who are the most likely stakeholders to report on the condition of the service, commonly when it is nonfunctional. However, these consistent factor rankings appear to be the exception, as most factors show a wide range of rankings for dependence.

Overall, while the factors generally align with the WASH sectors' perception of the critical elements required to sustain services [79] the large range of influence and dependence factor ranks shows that these leverage point attributes have little consistency for factors across the four contexts. Overall, 79% (11/14) and 71% (10/14) of factors had a range of 25% or larger (a quarter of possible rankings) for influence, and dependence, respectively.

3.4. Feedback Loops

Using the connections of factors identified in the cross-impact matrix, a list of all possible feedback loop combinations beginning and ending at the outcome factor (*Sustainable Services*) was generated for each context. In total, this produced 691,449 unique feedback loops. Normalized scores for feedback loops were then quantified using values from the indirect cross impact matrices (MICMAC). The feedback loops were then ranked by these values and the top 1000 loops from each workshop were used to compare findings across contexts.

Of the resulting top 4000 loops, most were composed of five or more factors (64%), with 25% containing four factors. The remaining 10% of these loops consisted of two to three factors, with one-factor loops (one factor plus the outcome factor) comprising less than 1% of all loops. Overall, this suggests that the processes that drive rural water service sustainability outcomes involve a considerable number of cause-and-effect relationships, highlighting the need for a deeper understanding of interactions between factors.

Assessment of the third leverage point criteria—a factor's role in prominent feedback loops (Table 3)—showed that *Coordination* was the most frequently present factor, when adjusting for the number of contexts in which the factor was identified by workshop participants. The analysis revealed roughly three classes of factors; those which were present in more than half of the possible contexts, (*Financing, Users, Local Capacity, Hardware, WRM, Regulations*), those that were present in less than half (*Community, O&M, Planning, Mechanics*), and those that were rarely present (*Politics, Monitoring*). Most notable of these findings is that the most highly ranked factor for influence, *Community*, was present in nearly half (49%) of the loops in the two contexts where it was identified by participants. Conversely, the least dependent (most independent) factor, *Monitoring*, was present in less than 10% of the three contexts where it was identified by participants.

Table 3. Relative presence and frequency of common factors in top-ranked feedback loops in contexts for which the factor was included in the cross-impact matrix.

Rank	Factor	# of Loops (%)	# of Contexts
1	Coordination	2230 (74%)	3
2	Financing	1919 (64%)	3
3	Users	1870 (62%)	3
4	Local Capacity	1206 (60%)	2
5	Hardware	1195 (60%)	2
6	WRM	1186 (59%)	2
7	Regulations	1570 (52%)	3
8	Community	974 (49%)	2
9	O&M	1343 (45%)	3
10	Planning	690 (35%)	2
11	Mechanics	1029 (34%)	3
12	Politics	354 (12%)	3
13	Monitoring	261 (9%)	3

Note: The outcome factor Sustainable Water Services is not shown here as it is present at the beginning and end of all feedback loops.

3.5. Common Feedback Loops

In addition to the presence of factors in feedback loops, we also assessed how common or unique individual feedback loops were across the four contexts. We found that only 17 of the top 4000 loops (0.4%) were common to two or more contexts (Table S4). In contrast to the full set of feedback loops, common loops were more likely to be composed of less factors; one (18%), two (24%), three (35%) and four (24%). The most common factors in the common loops included *Coordination* (10) and *Financing* (10), followed by *Local Capacity* (7) and *Water Resource Management* (7). In total, 10 of the 14 common factors were present in any of the common feedback loops. Additionally, while the top three loops each showed a relatively high ranking across contexts (average of two contexts), there was otherwise a wide range of rankings for the loops within each context where they emerged. This shows that while many factors were common to the four contexts (see Figure 1), no clear pattern emerges from the analysis of the feedback loops which suggests that any combination of factors may be more dominant across any given context.

3.6. Leverage Point Evaluation

Drawing on the three analyses of leverage point criteria (influence, dependence, presence in feedback loops), we find little evidence for the potential of any factor to consistently act as a leverage point across the four contexts (Figure 3). These findings hold within and across contexts (Table S5, Table S6), suggesting that leverage points in WASH systems are highly context-specific. For example, the *Community* factor was the second most influential and least dependent factor, but only present in half of the feedback loops where it was included in the cross-impact matrix. Similarly, while the *Financing* factor was the least dependent (most independent) factor across context, and the second most frequently present factor in feedback loops, it was ranked in the middle of the influence scores, suggesting that financing has a moderate ability to affect the state of the system on a whole. Conversely, factors such as *Monitoring*, *Politics*, and *Mechanics* appear to be weak leverage points for systems change. While these factors are fundamental elements of a strong system for sustainable WASH services, their individual ability to catalyze large scale changes in community-based management schemes appears to be secondary to the role of factors such as *Community*, *Regulations* and *O&M* (Figure 3).

The high influence and dependence ranking for the outcome factor—*Service Sustainability*—suggest that the current state of services can have a substantial effect on the system, even if it is reliant on all the other factors to support that service. While this suggests an important feedback effect that is often overlooked in the sector, it is difficult to discern its role in driving feedback behavior overall as

we only looked at loops that began and ended at the outcome factor, thus it is present in all feedback loops analyzed.

Factor	Influence	Dependence	Feedback
Service Sustainability	1	4	-
Community	2	14	8
Regulations	3	9	7
Planning	4	8	10
Operation & Maintenance	5	3	9
Local Capacity	6	11	4
Financing	7	1	2
Coordination	8	2	1
Users	9	5	3
Hardware	10	6	5
Water Resource Mgmt	11	7	6
Mechanics	12	10	11
Monitoring	13	13	13
Politics	14	12	12

Figure 3. Factors by average ranking of three leverage point criteria: influence ranking, dependence ranking, frequency in feedback loops. Scaling for dependence ranking is reversed, to signify that a lower ranking (more independent) represents a more desirable outcome (more versus less independent). List sorted by influence ratings (high to low).

4. Discussion

The analysis of the factor mapping workshops identified a general consensus amongst local stakeholders regarding the key factors needed to sustain services; however, the ‘roles’ that these factors play in supporting services had very little consistency across contexts. The common factors that were identified closely align with elements of sustainability frameworks [13], suggesting that local stakeholders are generally in consensus with one another and the WASH sector on the most important factors for rural water service sustainability. However, the quantitative and qualitative descriptions provided by workshop participants of how these factors influence other factors resulted in substantially different rankings for factor influence, dependence and presence in feedback loops across contexts. Indeed, while some factors were on average more influential (e.g., *Service Sustainability*, *Community*, *Regulations*) or less dependent than others (*Politics*, *Monitoring*, *Community*), there was little consistency in these findings across the four contexts. Additionally, the majority of influence and dependence factor ratings had a variability of 25% or larger across the four contexts. This suggests a wide range of roles that each of the common factors play in supporting service sustainability.

These findings were supported by the feedback loop analysis which showed that some of the most frequently present factors (*Financing*, *Coordination*, *Users*), were also some of the most dependent. These factors were also only moderately influential, indicating that they are in a relatively weak position to leverage a small change into a larger impact on the system as a whole. Considering the three leverage point criteria of influence, dependence and feedback together, the findings indicate that factors that act as the driving forces and potential areas for leverage in sustaining rural water services are likely highly context-specific.

These results are consistent with those obtained by the common feedback loop analysis, which showed that only a very limited number of feedback loops are common across contexts. Despite drawing on the same set of factors, only 17 of 4000 feedback loops were common across contexts, drawing on a total database of 691,449 unique feedback loops. Overall, of the large number of possible pathways of factors that could either sustain or diminish water services, no individual factor(s) or feedback loop(s) appears to consistently be more critical than any others in influencing the sustainability of water services.

The differences in how factors are connected across contexts, and the wide variety of feedback mechanisms they form to support sustainable services, suggests that the behavior of these factors and their interactions is consistent with some of the key characteristics of complex systems. This does not indicate that the systems that support rural water services are entirely unique, as we found many factors to be common across contexts and aligned with the key elements identified by the WASH sector [52]. Rather differences in the relative strength of factors' influence on service sustainability may indicate a level of adaptation of local complex systems wherein the same 'building blocks' of service delivery are necessary in each context, but the structure through which they are connected is specific to the social, economic and environmental conditions in which the service is delivered. This supports a conceptualization of WASH services as complex adaptive system that evolves over time to a given context [18].

Overall, these findings suggest that recent trends in systems approaches to understanding WASH services may be overlooking the impact of systemic factor interactions by assuming that factors have consistent relationships with one another across different social, geographic and political landscapes. The consequence of this assumption can be seen throughout the WASH sector where programs that were successful in one context fail to produce consistent impacts when they are scaled-up, or spread out, to seemingly similar contexts [1,80]. We contend that these results are likely the product of policies which fail to directly address the context-specific (weak) leverage points in a local system. To address this, we recommend that WASH sector professionals engage key local stakeholders in explicit discussions of factor interaction—either qualitative or quantitative—to better understand which factors in a given local context exert leverage on service delivery outcomes based on how they affect other factors.

To our knowledge, this is the first study to quantitatively analyze factor interaction and feedback mechanisms for rural water services across multiple contexts using a complex systems approach to understanding WASH services. We employed a novel process for engaging local stakeholders in structured discussions of complex systems across multiple comparable contexts to systematically evaluate differences in structure of systems that support rural water service sustainability. The resulting findings and discussion of leverage point potential are thus based directly on local perspectives and established structural factor analysis.

Limitations and Future Research

We intentionally bounded the scope of the factor mapping workshops to a geopolitical boundary to focus the discussion on the local system within which many of the participants are key decision makers. However, it is important to acknowledge that there are many elements of an enabling environment for sustaining rural water services that lay outside of this boundary, such as the role of national institutions, NGOs and donor organizations.

Additionally, the data collection approach we used represents, by its nature, a singular point-in-time snapshot of the system as described by the participants in the workshop. Thus, repeating the workshop at a different time with different participants would likely produce different findings. However, we found that participants across the four contexts tended to identify a common set of factors, defined in comparable terms. Additionally, the use of indirect matrices for assessing feedback loop dominance, and checking influence and dependence scores, limited the impact of individual factor-on-factor interaction ratings within the matrix. Thus, even though individual scores may differ, a cross-impact matrix mapped by two different groups of participants with comparable knowledge of services, using the same factors, in the same context would likely produce similar results due to the limited impact of individual interactions. However, despite these potential limitations, our team has observed the impact of the factor mapping process on improving participants' understanding of complex system [81], which has led to improved decision making on complex WASH systems issues [82], including the developed of a district-wide master plan for WASH in Kabarole District, Uganda [83].

To assess the impact of these limitations on the ability of factor mapping workshops to produce accurate and useful insights into WASH system complexity, our future research intends to evaluate

how relationships between factors change over time by repeating the workshop activity within the contexts presented in this work.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/12/3/1243/s1>, Table S1: Demographic context information; Table S2: Matrix of indirect influences (Kamuli example); Table S3: Factor names and definitions for all contexts; Figure S1: Factor influence and dependence rankings (Kamuli example); Figure S2: Cross-impact matrices by context; Table S4: Common feedback loops; Table S5: Influence, dependence and feedback rankings for common factor by leverage point criteria; Table S6: Influence, dependence and feedback rankings for common factor by context.

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