2015

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ARTICLE INFO

Article history:
Received 28 August 2015
Received in revised form 10 December 2015
Accepted 10 December 2015
Available online 22 December 2015

Keywords:
Sustainability
Rural water services
Nicaragua
Graphical modeling
Factor analysis
Networks

ABSTRACT

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

1. Introduction

The challenges of providing sustainable access to rural water services in developing countries often go far beyond that of the technology itself (Kaminsky and Javernick-Will, 2014). Indeed, many water systems (wells, gravity-fed systems, etc.) tend to fail or operate suboptimally due to a myriad of social, environmental and political factors that confound water service sustainability (RWSN, 2011; Lockwood et al., 2003; WaterAid, 2011; Davis, 2014). In most cases these factors are interconnected and interact as a system, producing outcomes that are often difficult to plan for or adapt to (WaterAid Malawi, 2003; Sara and Katz, 1997; WaterAid, 2011; Ramalingham et al., 2008; Ramalingham, 2014). While water sector literature has identified a number of important factors that affect the sustainability of rural water infrastructure, there is limited research that explicitly addresses the systemic nature of factor interactions. Improving understanding on how factors interact as a system would in turn enable practitioners to plan initiatives that target specific programmatic areas that yield the greatest overall impact on water service sustainability, which this study calls *impact factors*. Thus, the aim of this study was to rigorously investigate how factors that influence rural water service sustainability interact as a system.

The identification of influential factors for water service sustainability in the developing world, and the associated assessment and evaluation methods used to analyze the impact of these factors, has been the focus of many research efforts within the water sector over the past two decades. As a testament to this level of sector attention on sustainability, a recent study of both scholarly and non-scholarly water sector literature by Walters and Javernick-Will (2015) identified 93 articles that focused specifically on factors that influence rural water service sustainability. In their study they identified 157 unique factors mentioned to influence water service sustainability, and aggregated these factors into the 25 sub-factor groups and 8 "sustainability factors" shown in Table 1.

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Table 1
Summary of sustainability factors found in water sector literature (Walters and Javernick-Will, 2015).

Sustainability factor	Sub-factors
Government	Laws & policy
	Management
	Governance
Community	Participation
	Demand
	Satisfaction
External support	Type of support
	Cooperation
	Post const. supp.
Management	Maintenance
	Skilled operator
	Women involvement
Financial	Cost recovery
	Financial management
	Cost of system or part
Technology construction & materials	Spare part availability
	Tech. appropriateness
	Construction quality
Environment & energy	Resource management
	Source protection
	Energy availability/ Reliability
Water system functionality	Quality
	Quantity
	Reliability
	Coverage

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

Tabular analysis tools evaluate survey data by scoring and aggregating factors to derive a composite score commonly presented as frequencies, averages or percentages relative to some level or threshold of service sustainability (e.g., Hodgkins, 1994; WSp, 1996; Bhattarai, 2005; Sugden, 2001; WaterAid Malawi, 2003; Godfrey et al., 2009, 2013; Schweitzer and Mihelcic, 2012; USAID, 2013; Boulenouar et al., 2013). A major benefit of tabular analysis is that the data need not be directly measurable to evaluate sustainability, but instead may be interpreted by the researcher using a pre-defined scoring criterion. A major limitation of the tabular analysis methods is the inherent subjectivity that may influence the results, potentially making the data biased, and as a result, inaccurately representing the realities in the field.

Regression analysis techniques measure the significance of the relationship between one or more independent variables (i.e., factors) on one dependent variable (i.e., sustainability). Statistical techniques used by regression analysis are typically either bivariate or multivariate linear regression (e.g., Narayan, 1995; Sara and Katz, 1997; Mukherjee and Wijk, 2003; Foster, 2013). A major benefit of these techniques is their ability to identify the presence of correlations between factors in a way that limits bias and subjectivity on the part of the researcher. Unlike tabular analysis, however, regression analysis requires that all data be measurable, a point which frequently makes its proper use considerably more difficult and costly to conduct.

While both types of sustainability assessment techniques have unique strengths and weaknesses, one common weakness is the inability to evaluate or correlate the systemic interaction of factors (Sugden, 2001; Jordan et al., 2011). This systemic interaction may be thought of as a web of factor influences that are both *direct* (Factor A influences Factor B), as well as *indirect* (Factor A influences Factor C by first influencing Factor B). Therefore, an improved evaluation of sustainability would be achieved by considering these direct and indirect interactions (Sugden, 2003). Thus, this study aimed to advance understanding and practice on rural water service sustainability in developing countries by investigating a means to assess the factors that impact sustainability using a systems-based analysis.

To accomplish this objective, the technique developed in this study exploits the aforementioned strengths of both tabular and regression analysis by first collecting and analyzing case study data to find and score factors, and then uses these data to probabilistically identify systemic factor interaction and impact through graphical modeling and network analysis. More specifically, this study used qualitative and quantitative data analysis methods that culminated with *graphical modeling* to display the systemic interaction of influential factors in the form of *factor networks* . The techniques presented in this paper are demonstrated using a case study of rural water service functionality in Darío and Terrabona, Nicaragua. In this research, the term sustainability is reframed as the *long-term service functionality* of a particular type of water supply technology, based on water quality and service reliability. The following research questions that guided these research efforts were:

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

To answer these questions, data was obtained using semi-structured interviews with community water committee (CWC) members in charge of water system operation and maintenance in Darío and Terrabona Nicaragua. Interviews were first analyzed to identify recurring factors that appeared influential to long-term water service functionality. Graphical models then were used to graphically represent conditionally-dependent connections that existed between these factors as a way to build factor networks. Factor networks were then structurally analyzed using *point* and *graph betweenness centrality* measures to identify impact factors based on their overall connectivity within the network. These impact factors were then used to inform potential program strategies for rural water services in Darío and Terrabona.

2. Research methodology

This research employed a multi-method approach that culminates with graphical modeling to build factor networks, and used network analysis to structurally analyze these networks to find the most impactful factors on long-term water service functionality in Darío and Terrabona, Nicaragua. The requirements for graphical modeling and network analysis guided the selection of the research methods. First, interviews and community water system assessments were conducted with CWCs in Darío and Terrabona, Nicaragua. Second, these data were qualitatively coded to identify pertinent factors (addressing RQ1), which were then quantitatively categorized as binary variables to aid in graphical modeling. Third, these data were entered into a graphical modeling software, which iteratively built dependence graphs to display the interaction of factors within factor networks for both Darío and

Terrabona (addressing RQ2). Lastly, these factor networks were visually and structurally analyzed to infer factor importance based on betweenness centrality (addressing RQ3), thereby facilitating a thoughtful discussion on unique water planning strategies for both Darío and Terrabona (addressing RQ4).

2.1. Data collection–case study

The municipalities Terrabona, and Ciudad Darío (Darío), Nicaragua were chosen for this study because of compelling differences in population size, improved water coverage, stakeholder management schemes (municipal governments, non-governmental organizations, CWCs, etc.), and a large difference in long-term water service functionality, despite their close proximity (16 kilometers). Historically, Darío has had far greater access to financial and material resources than Terrabona. As a result, Darío has installed water systems in over 90% of the communities within the municipality, compared to 77% coverage in Terrabona. A comparison between a few distinct municipal attributes as they relate to the percentage of improved water infrastructure coverage, along with the percentage of water systems that were found to properly function based on a recent study by El Porvenir (2013), are shown in Table 2. The term "improved coverage" implies the community water system prevents outside contamination of the water source (WHO and UNICEF, 2015). In Darío and Terrabona, the predominant technology for improved water coverage is in the form of either rope-pumped wells or piped gravity-fed systems (El Porvenir, 2013).

The *case study* research method using qualitative data collection and analysis was deemed well suited for collecting data to explore the factors that influence long-term water service functionality in Terrabona and Darío (Yin, 2002; Maxwell, 2004). A multiple-site case study scheme was chosen to obtain data that was spatially and contextually interesting, conjointly providing a more compelling and robust foundation for the propositions made within the data analysis and interpretation process (Yin 2002; Herriott and Firestone, 1983). Each case study followed an embedded multi-case scheme, where the embedded unit of analysis was set at the community level (Yin, 2002). In each of the municipalities, data were collected in the form of semi-structured interviews with CWC members, and through detailed observations taken while in each community. CWCs are composed of elected members from the community who are in charge of the basic operation and maintenance of the community water system. Throughout the three-month case study time period, it was possible to visit 32 randomly sampled communities in Darío and 22 in Terrabona.

Interview questions were intentionally kept open-ended and directed towards identifying the presence of factors that influence the long-term functionality of rural water infrastructure within each sampled community. The influence of a particular factor was noted to exist if the interviewee indicated it influenced the long-term functionality of the water service. For example, questions were asked such as, "how well is your water system functioning?", and, "have there been situations where the water system is not functioning properly? If so, why?" These types of questions allowed CWC members to tell meaningful stories about how their water system had been functioning over the long-term, and provided the necessary data for qualitative analysis used to illuminate the important characteristics of impactful factors on long-term water service functionality.

Table 2
Terrabona-Darío comparison.

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

Observational data was gathered in the form of water quality tests and detailed field notes. These data served to compare and contrast the time-based progression of water system functionality inferred from the interview data with the present functional state of the water system, and to provide additional contextual depth to critically evaluate the research findings, respectively. Water system functionality data was specifically: water reliability (how often the water system was out of service), and water quality. System reliability was assessed by asking interviewees to indicate how often the water system was typically out of service each year. Water quality was evaluated by water quality tests and the identification of potential pollution risks (presence of nearby animals, pit latrines, etc.). Water quality at the time of sampling was based on the presence or absence of fecal coliforms using PathoScreen Field Test Kits (Hach, 2015).

2.2. Data analysis–factor quantification

Audio recordings of CWC interviews were transcribed and then analyzed for emerging themes through *descriptive qualitative coding*, following the "two-cycle" coding process recommended by Miles et al. (2014). This process entailed identifying portions of transcribed text that fit within recurring themes and patterns, paying special attention to factors that appeared to influence the long-term functionality of water services. Codes were then aggregated into themes and then into factor groups to allow conversion of the data into a quantitative format necessary for graphical modeling.

The quantitative format for the data was chosen as binary, either "yes" (1) or "no" (0) for each factor. This process was chosen to minimize subjective scoring and subsequent bias on the part of the researcher. For example, if a reason given by an interviewee for why their water system was not functioning properly was the "insufficient maintenance and financial support due to frequent conflicts between community members"—the associated factor "conflicts" would be marked as "yes" (1) for that particular community sampled. In a similar way, if the same community experienced seasonal fluctuations in groundwater level, which often caused water shortages, the factor "water resources" would be marked as "yes" (1) for that community. What resulted from this qualitative analysis was a list of recurring factors that emerged between each community, where the presence or absence of each factor was designated as either "yes" or "no" for each community.

2.3. Data analysis–graphical modeling and factor network analysis

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

In graphical modeling, *log-linear models* are typically used to fit discrete data when there is no clear distinction between

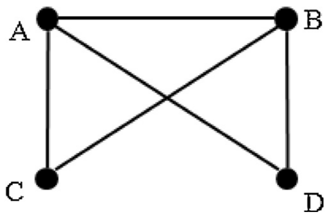

Fig. 1. An example graphical model.

independent and dependent variables (Whittaker, 1990; Edwards, 2000). Since the quantified factor data in this study were discrete (binary) data, and factor dependence and independence were unknown, a log-linear model was used to fit these data sets. One of the primary difficulties with using graphical modeling to fit a multivariate data set, is choosing between a myriad of different well-fitting model structures (Whittaker, 1990). In the case of even a 15 node undirected graph (a model where edges are not explicitly directional), the number of possible undirected graphs is 4.05×10^{31} (Højsgaard et al., 2012). Thus, the likelihood of having the true best-fit model is small, especially when the number of variables is high. However, in the case of this research, a best fit was deemed less important than a "good fit" model that provided insight into the implication of systemic factor interaction (Amadei, 2015).

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

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

Betweenness centrality scores were calculated both for the factors themselves (known as *point centrality*) as well as for the entire graph (known as *graph centrality*). Point centrality (from this point forward referred as *factor centrality*) scores were calculated for each factor to allow for factor comparison to identify impact factors. Calculation of factor centrality scores was accomplished by analyzing the resulting *adjacency matrix* for each graphical model using the R-package *statnet* (Acton and Jasney, 2012). The equation used to calculate a betweenness score for an undirected graphical model is shown below. Betweenness scores for Terrabona and Darío graphical models were then ranked from high to low to allow a basis for score comparison using Eq. (1):

$$C'_B(p) = \sum_{o \neq p \neq q} \frac{\sigma_{oq}(p)}{\sigma_{oq}} \quad (1)$$

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

Graph centrality (from this point forward referred to as *network centrality*) allowed for additional structural comparison between the factor networks themselves, built for Darío and Terrabona, based on the normalized distribution of betweenness centrality scores in each network (Freeman, 1979). Calculation of network centrality required the use of factor betweenness centralities $C'B(p)$, for each graphical model. These factor betweenness centralities were used to find network centralities for Darío and Terrabona using equation 2 below, which compares the largest factor betweenness score within a factor network with all other scores in the network (Freeman, 1979).

$$C_B = \frac{\Sigma_{i=1}^{n}[C'_B(p^*) - C'_B(p_i)]}{\max \Sigma_{i=1}^{n}[C'_B(p^*) - C'_B(p_i)]} \quad (2)$$

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

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

3. Results & discussion

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

3.1. Factor identification and quantification

The transcribed interviews in combination with field observation allowed for the coding of recurrent themes for why (or why not) a water service had been functioning in communities in Darío and Terrabona. Recurrent themes were coded because they signified factors that were consistently important for long-term water system functionality; and because graphical model building required the use of consistent factor comparisons for each sampled community to evaluate conditional dependence between factors. Themes of interest related specifically to aspects that appeared to enable or hinder the long-term functionality of the community water service. For example, an important recurring theme in both Darío and Terrabona – community *organization* – appeared to influence the community's ability to make timely and effective water system repairs, as mentioned by one water committee member:

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

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

> *"If the rope pump breaks, then we go house by house to collect 5 pesos from each house, and when it's more, 20 pesos per house, and in this way, we buy the necessary parts to fix the pump."*

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

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

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

3.2. Analysis of factor networks

By identifying and quantifying factors in binary terms, it was possible to build graphical models to represent factor interaction for Darío and Terrabona. The factor networks that emerged from these analyses for Terrabona and Darío are shown below in Fig. 2 . In these networks, the circles represent factors and the lines represent a conditional dependence used to indicate influences between two factors.

Visual interpretation of factor networks, along with the structural analyses of these networks using betweeness centrality, provided useful insight about factor interaction and importance. Regarding the former, the factor networks presented in Fig. 2 facilitated the inference of direct (bold lines) and indirect (faint lines) influences between each of the factors on *Water System Functionality* (WSF) to characterize potential pathways for or against long-lasting water services. For example, in the case of Darío, Fig. 2 (left) shows that *Water System Functionality* is directly connected to *Management* and *Community*, implying the efficacy of a water service management plan, and level of community organization, have a direct influence on water service functionality in Darío. This means that water service management and community organization could conceivably be targeted by practitioners to directly influence long-term access to services. However,

Table 3
Coded themes.

Themes	Definition
Organization	Organization of the community (i.e., regularly holding and attending meetings to discuss aspects of water system maintenance)
Conflicts	People refusing to pay their user fees and associated problems with tariff collection and saving
Source protection: cleanliness	Cleanliness around the water source (i.e., presence of garbage and waste that could seep into the water table)
Source protection: fenced	Area around the source is fenced off from animals to avoid fecal contamination
Source protection: forested	Area around the source is forested to ensure an accessible water table
Government support	Consistent support offered by the government (i.e., technical, financial, and training and education)
Water committees	The existence of a CWC to manage the water services
Road conditions	Access to viable transportation into and out of community year round to acquire necessary materials for water system maintenance and repair
Material availability	Access to quality construction and repair materials
Appropriate technology	Technology that is affordable for the community
External support	Consistent support from an outside organization (i.e., technical, financial, and training and education)
Tariff payment	Monthly collection of user fees to maintain sufficient savings
Sufficient savings	A savings account to pay for system maintenance and repairs
Water shortages	Reliability of the service in providing water all year round
Water quality	Water quality based on the presence of fecal contaminants

Table 4
Factors.

Factor	Associated theme	Criteria	
		yes	no
Water system functionality	Water quality and reliability	both	<Both
Community	Organization of the community: regularly holding and attending meetings	Yes	No
Government	Community frequently receives help from government	Yes	No
External support	Community frequently receives help from organizations	Yes	No
Finances	Regular collection of monthly user fees, and sufficient savings	Both	<Both
Water resources	Protection of the source: clean surrounding, fenced and well-forested	All 3	<All 3
Technology	Appropriate technology: viable supply chain and cheap materials	Both	<Both
Infrastructure	Viable transportation into and out of community all year	Yes	No
Management	Existence of a well-organized community water committee	Yes	No

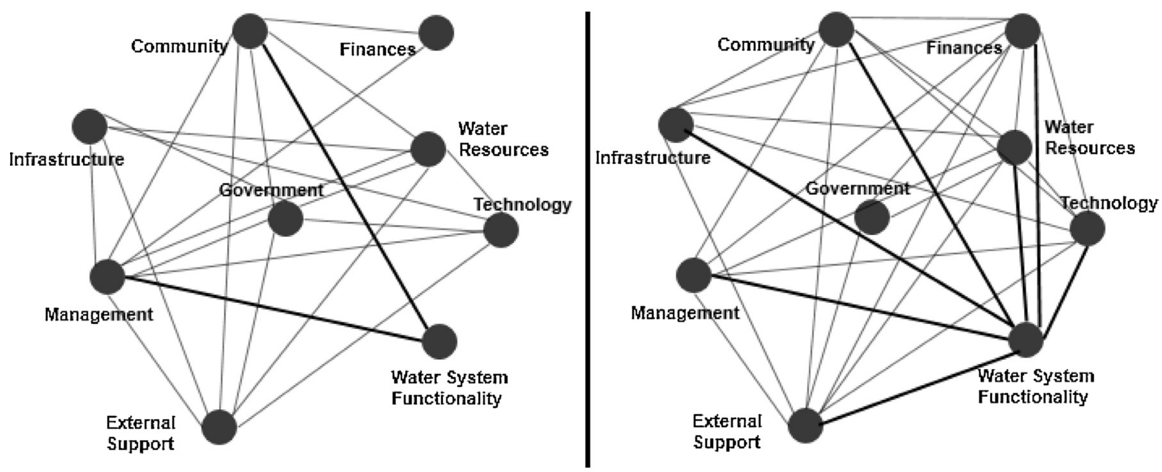

Fig. 2. The factor networks for Darío (left) and Terrabona (right), direct influences on water system functionality are in bold.

Fig. 2 (left) also shows a large number of factors that both directly *and* indirectly influence both *Management* and *Community* (and thus *Water System Functionality*) through numerous distinct pathways. As a result, targeting impactful program areas in Darío could prove difficult based solely on this present analysis of direct and indirect factor interaction. Similarly, visual analysis of Terrabona's factor network in Fig. 2 (right) reveals the majority of factors interact directly with *Water System Functionality*, in the same way suggesting a large number of influential pathways on long-term service functionality. Thus, while observation of direct and indirect influences allows for the development of meaningful conclusions regarding potentially influential pathways towards long-term water service functionality, it is apparent that further structural analysis is needed to explicitly identify the most impactful factors.

This need for additional information on impact factors is addressed here by applying betweenness centrality scoring and ranking for both factors networks. These ranked betweenness centrality scores are presented in Table 5, where higher factor centrality scores imply higher importance or impact for these factors due to their intrinsic ability to bridge and form pathways between other factors that influence *Water System Functionality*. For Darío, the factors *Management* (ranked 1) and *Community* (ranked 2) emerge as the most impactful factors. In the case of Terrabona, *Water Resources, External Support* and *Finances* were found to be most important (ranked 1), whereas compared to

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

Rank	Darío[a]		Rank	Terrabona[b]	
1	Management	4	1	Finances	1.833
2	Community	2.75		Water resources	1.833
3	Water resources	1.417		External support	1.833
	Government	1.417	2	Community	0.166
	External support	1.417		Water system functionality	0.166
4	Water system functionality	0		Technology	0.166
	Finances	0	3	Infrastructure	0
	Infrastructure	0		Government	0
	Technology	0		Management	0

Normalized network centrality score.
[a] 0.1317.
[b] 0.0234.

Darío, *Community* was found to be relatively less impactful given a lower factor centrality and overall rank.

Additional distinctions may be made between the factor networks by analyzing overall network centrality scores for Darío (0.1317) and 0.0234 for Terrabona (0.0234). These value differences of nearly an order of magnitude imply a higher potential to target impactful program areas in water service in Darío relative to Terrabona, where the same task of targeting impactful program areas would likely be more difficult. In other words, because the Darío network has a higher factor centrality scores overall, it would conceivably be easier to identify areas where strategic programmatic changes would have the greatest impact, since *Management* and *Community* are clearly the top-ranked factors, yielding significantly higher centrality scores relative to the other factors. Conversely, it would be considerably more difficult to locate impact areas for Terrabona given the existence of three factors in the top ranks (*Finances, Water Resources, External Support*), all of which have markedly lower overall betweenness (i.e., impact) scores compared with the top-ranked factor scores in the Darío network.

These outcomes based on factor network structure, when compared with observations in the field, imply the need to approach water service programming in these two locations in a very different manner. In fact, interesting similarities were found to exist between what was observed in the field, and the findings inferred by the factor analyses. These similarities both validate the study findings and enable the tailoring of thoughtful suggestions on particular programmatic recommendations for Darío and Terrabona. For example, Darío has historically had greater economic prosperity, and in essence, is in a different stage of development than Terrabona. As a result, the local government and organizations in Darío have had the capacity to invest in the implementation of water services, as well as CWC training programs. Thus, at the current phase of development in Darío, the crucial elements for sustained water services would logically hinge on effective *management* of the water services by each community's CWC. This claim is supported by a quote from a CWC member in Darío where a water system had been continually functioning for over 10 years:

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

Conversely, as a poorer municipality, Terrabona has historically had lower access to financial and material resources, and correspondingly has installed less water infrastructure. This reality currently places them in a different phase of development than Darío, one which the associated impact factors logically hinge on the need for reliable and clean water sources, viable finance planning, and external support to act as a catalyst to provide access to water services. Thus, while management and community involvement are certainly important in Terrabona, perhaps more important currently are the more rudimentary components for water service access (i.e., the identification of viable water sources) along with effective external support from the local government or organization. Indeed, while many water systems in Terrabona were seen to have issues with overall functionality, those that were most successful had high levels of external support to provide money and resources towards existing water services, as well as offering workshops for CWCs on proper water system maintenance. As one CWC member in Terrabona remarked:

> *"Last year our water system had issues with broken pipes and sand clogging the system. But, thanks to a local organization – who provided help with money and new tubes to fix the problem, as well as training on maintenance – the water system is working again. They also continue to provide workshops to help us learn more about maintaining the system to avoid this happening again."*

These parallels between field observations and the factor analyses presented here, support compelling insight into programmatic changes that could target potential impact factors through policy or direct implementation of water service management strategies in Darío and Terrabona. In the case of Darío, it currently appears advantageous to invest resources in continuing to build CWC capacity to manage water services. Currently, in Terrabona, further external support appears necessary to first elevate the level of water service access, and then fortify CWC management capacity in a similar way as Darío, to better operate and maintain water services.

4. Conclusions & study implications

This study presented a means to rigorously identify, visualize, and analyze the systemic interaction of factors that influence the long-term functionality of rural water services in Nicaragua. This methodology was demonstrated through a case study conducted in Darío and Terrabona Nicaragua with the aim of understanding factor interaction and importance to identify impact areas for strategic planning and management of rural water services in these two municipalities. In this multi-method study, qualitative data collected from community water committee (CWC) interviews were coded and analyzed to allow important factors to emerge. These factors were then quantified into a binary format and analyzed with graphical modeling to build factor networks used to display factor interaction and identify impact factors.

Analysis of these factor networks showed marked structural differences for Terrabona and Darío. Specifically, preliminary analysis of factors by visually identifying direct and indirect influences on water system functionality, revealed water services in Darío were directly influenced by proper service management and community organization; while in Terrabona, the majority of factors were found to directly influence water system functionality, thereby prohibiting formation of meaningful conclusions. Overall, the direct and indirect analysis of factor influence within these factor networks pointed to the need to prioritize factor importance as a way to target program areas with the highest potential for impact.

To unearth factor importance, factors within each factor network were scored and prioritized using betweenness centrality measures of the factors themselves, along with scoring the overall network structure using network centrality. For Darío, the two highest ranking (and therefore highest impact) factors were *Management* (ranked 1) and *Community* (ranked 2), meaning the presence of a well-organized CWC and community would be most impactful on long-term water service functionality. For Terrabona, however, three factors held the top rank: *Finances*, *Water Resources*, and *External Support*. Based on the factors characterized in this study, this suggests the most impactful factors on long-term water service functionality in Terrabona are sufficient funds to operation and maintain water services, viable water sources, and ultimately aid of external support to help with the initial stages of service implementation and management.

The implications of these results indicate a substantial difference in where practitioner should allocate resources in each municipality, and suggests that practitioners working in Darío should focus on ensuring CWCs are adequately organized and able to manage their water services. Conversely, practitioners in Terrabona would need to focus first on identifying feasible water sources, viable finance schemes, and effective external support opportunities provided by the local government and organizations.

In summary, this study presents a practical tool to infer the systemic interaction of factors that influence rural water services sustainability in a developing world context. Through the intersection of systems tools such as this in future research, it will become increasingly more attainable to analyze the inherently interrelated nature of complex issues inhibiting rural water service sustainability, and allow policy makers and practitioners to focus on the areas with the greatest opportunity for impact.

Acknowledgments

This work was supported by a Graduate Research Fellowship from the Mortenson Center in Engineering for Developing Communities at the University of Colorado Boulder.

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