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SUSTAINABLE WATER AND SANITATION SERVICES
FOR ALL IN A FAST CHANGING WORLD

Performance evaluation of community managed
water supply infrastructure

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This paper presents data and analysis from a two-year study, which was aimed at investigating the sustainability of community, managed water supply infrastructure in Nicaragua and Panama. Sustainability, as defined by this study was evaluated using performance monitoring of water quantity, water quality and reports from water management committees on system reliability. The long-term objective of this study is to investigate system performance as a function of social, technical, environmental, economic and political constraints. This paper presents the techniques used to measure system performance.
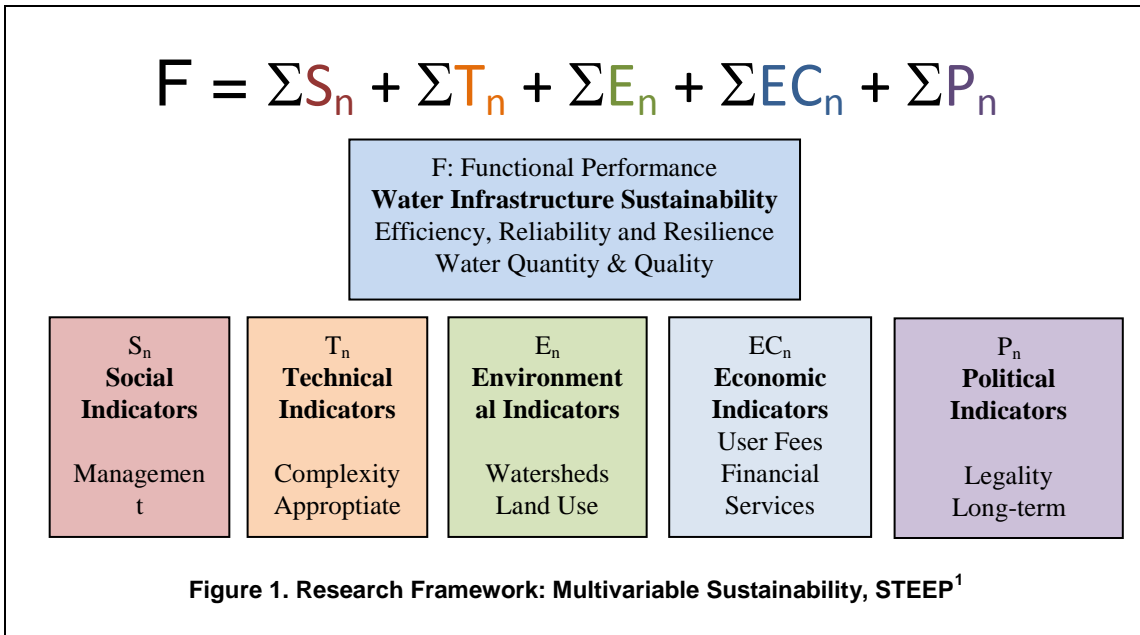
System performance: sustainability, reliability and resilience

Sustainability is a broad subject area that is complex, interdisciplinary in nature and has as many as 300 definitions (Dobson, 1998). A common reference to sustainable development entails a framework that was established in 1994 by John Elkington, which is known as triple bottom line sustainability; Social, Economic and Environmental Sustainability. Within the water supply sector in developed countries such as the United States, environmental sustainability has been an important aspect of delivering reliable services. This, along with a strong regulatory framework, has required water utility companies in industrialized areas to focus equally on all aspects of the triple bottom line. Another commonly accepted definition of sustainable development is, "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987). Within the international water and sanitation sector (WASH), regulatory issues, institutional support, management and lifecycle cost have been key elements of the sustainability discussion (JMP, 2012).

As a result, a single universally accepted definition of sustainability is not available and each sector has defined the term accordingly. This research study proposes that sustainability, reliability and resilience are interrelated, and adopts the definition that; sustainability is "whether or not something continues to work over time" (Abrams, 1998). A similar definition has been established by IRC's International Water and Sanitation Centre, and states that; sustainability is "the indefinite provision of a water service with certain agreed characteristics over time" (Lockwood, 2011). In this study, the "agreed characteristics" are being defined in terms of water quality and quantity. In short, the reliability of water supply infrastructure is being investigated with respect to supplying access to safe drinking water. This study incorporates the terminology of reliability in reference to system performance and uses the term sustainability to reference external inputs to the implementation process. The term resilience is used with respect to the systems ability to recover from unusual external influences like extended periods of dry weather, mismanagement of community funds or natural disasters and other environmental calamities.

Figure 1 shows the research framework used in this study that includes a multivariable analysis of sustainability as it relates to the reliability and resilience of water supply infrastructure in developing communities. The proposed framework includes lessons learned from experience and a comprehensive review of existing literature. This paper presents the monitoring and evaluation techniques that were used to measure system performance in terms of water quantity and water quality. The overall objective of this research is to investigate relationships between system performance and sustainability indicators or external

inputs to the process of implementing a community-managed water supply project. External factors have been defined using Social, Technical, Environmental, Economic and Political variables that potentially influence infrastructure performance (STEEP Framework[1]). In order to investigate the influence of external factors, clearly defined metrics for evaluating system performance are essential. This paper presents the field techniques used to monitor the functional performance of water supply infrastructure in terms of both water quantity and water quality. Water quantity is defined as the ability of the system to delivery water and is expressed in terms of delivery efficiency. Water quality is defined in terms of the systems ability to provide clean water and is expressed in terms of compliance efficiency. The reliability is the overall system performance and represents the ability to provide both water quality and water quantity.

$$F = \Sigma S_n + \Sigma T_n + \Sigma E_n + \Sigma EC_n + \Sigma P_n$$

F: Functional Performance
Water Infrastructure Sustainability
Efficiency, Reliability and Resilience
Water Quantity & Quality

S_n **Social Indicators**	T_n **Technical Indicators**	E_n **Environmental Indicators**	EC_n **Economic Indicators** User Fees	P_n **Political Indicators**
Management	Complexity Approptiate	Watersheds Land Use	Financial Services	Legality Long-term

Figure 1. Research Framework: Multivariable Sustainability, STEEP[1]

Methodology

This study measures the efficiency of water delivery systems, by evaluating the percent empty conditions within water storage facilities, using a 25% criteria. The water quality compliance efficiency is defined as the percentage of water samples taken throughout the system that comply with selected WHO Water Quality Standards. The total system performance, or the reliability of the system is determined by multiplying the quantity and quality performance-efficiencies. Quantitative data was collected and analysed at six piped water supply systems in Panama and Nicaragua (Table 1). The site selection criteria included locations that were familiar to the research team and that had an existing community managed piped water supply.

System efficiency for water delivery was evaluated by installing monitoring equipment within the water storage facilities to record water levels on a fifteen-minute time interval. The maximum water levels recorded for each water storage tank were used to define the 25% (empty) and 75% (full) values. The tank-full conditions (F) was defined as water levels greater than 75% of the maximum water level in the data set and tank-empty conditions (E) was defined as water levels that are less than 25% of the maximum The reliability of the water supply infrastructure studied in this project with respect to the delivery of water, or water quantity is defined as, one minus the percent empty value using a 25% water level criteria ($\eta_{del} = 1 -$ PE25).

Water quality was evaluated throughout the system including household level sampling as well as source and storage tank sampling. The system performance for water quality (η_{WQ}) was determined by analyzing samples for physical, chemical and biological contaminants. Total coliforms and e-coli were analysed using Petrifilm[TM] microbial tests and were evaluated using a criterion of less than 10 CFC/100ml and 1 CFC/100ml respectively. Nitrates (10 mg/L-NO3 and 1 mg/L NO2), Total Dissolved Solids (1000 mg/L), Hardness (200 mg/L) and pH (6.5 – 8.5) were analysed using commercially available test strips. Standard field techniques were employed for the purposes on ensuring accuracy and included the use of blanks and duplicates for analytical procedures. The analysis of all samples was conducted within a 24-hour period of sampling and total coliforms and e-coli required incubation for 24 and 48 hours respectively. The

performance efficiency for water quality (η_{WQ}) is defined as the percentage of total water tests within a single water supply, in compliance with the above standards. This approach does not take an average of single sample compliance to report the water quality performance efficiencies.

The total system reliability score (η_{sys}) was determined by multiplying the performance efficiency for water delivery (η_{del}) and the water quality compliance efficiency (η_{WQ}). If a water supply had a water quality compliance efficiency score of 0.90 and a water delivery efficiency of 0.95 then overall system reliability score ($\eta_{sys} = \eta_{del} \times \eta_{WQ}$) would be 0.855, or 85.5%.

Table 1. Summary of project site characteristics			
Site location and infrastructure type	**Total system beneficiaries (households)**	**Total storage volume (litres)**	**Distribution system length (meters)**
Upper - Santa Maria, Nicaragua (U-SMK)	56	8,000	3,500
Lower – Santa Maria, Nicaragua (L-SMK)	23	10,000	2,000
El Guabo, Nicaragua (ELG)	45	18,000	5,500
Yaro, Nicaragua (Yaro)	51	18,000	7,500
La Florida, Panama (LaFL)	83	18,000	2,500
Parque Natural San Francisco, Panama (PNSF)	166	40,000	11,000

Results and discussion

The results presented in this paper include data from October 2013 to February 2014. Table 2 shows a summary of the analysis for the six projects studied. A statistical summary is shown to validate that, the approach taken did not show large deviations from the average or the median values. From a practical point of view, this information would be used to identify failed or failing systems. This information would also be used to verify assumptions made about seasonal variations in supply and demand, as well as assumptions made during the design phase. A root-cause analysis using the STEEP framework would be used to identify reasons for system failure and to establish best practices in Sustainable WASH. At the community management level, this information would be used to anticipate problems and to facilitate discussions about the resilience and reliability of water supply infrastructure.

Water delivery: The Water Delivery, or water quantity score compares the system's ability to continuously supply water to its intended beneficiaries. The highest scoring system with respect to water delivery was at Parque Natural in Panama, which was evaluated at 100 percent performance[2]. The lowest water delivery performance was at La Florida, Panama with an efficiency of $\eta_{del} = 44.8\%$[3] and the next lowest score was in the community of Yaro, Nicaragua at $\eta_{del} = 72.8\%$. Assuming 70% as a threshold criteria these results would suggest that La Florida is a failed system and Yaro is in danger of becoming a failed system. Figure 2 shows the water level data for the Yaro system and reveals a period of 32 days when the water levels were consistently below average. The data from Figure 2 can ultimately be combined with the tank dimensions to make better estimates of source supply flowrate and can also be used to determine peak demands for design purposes[4].
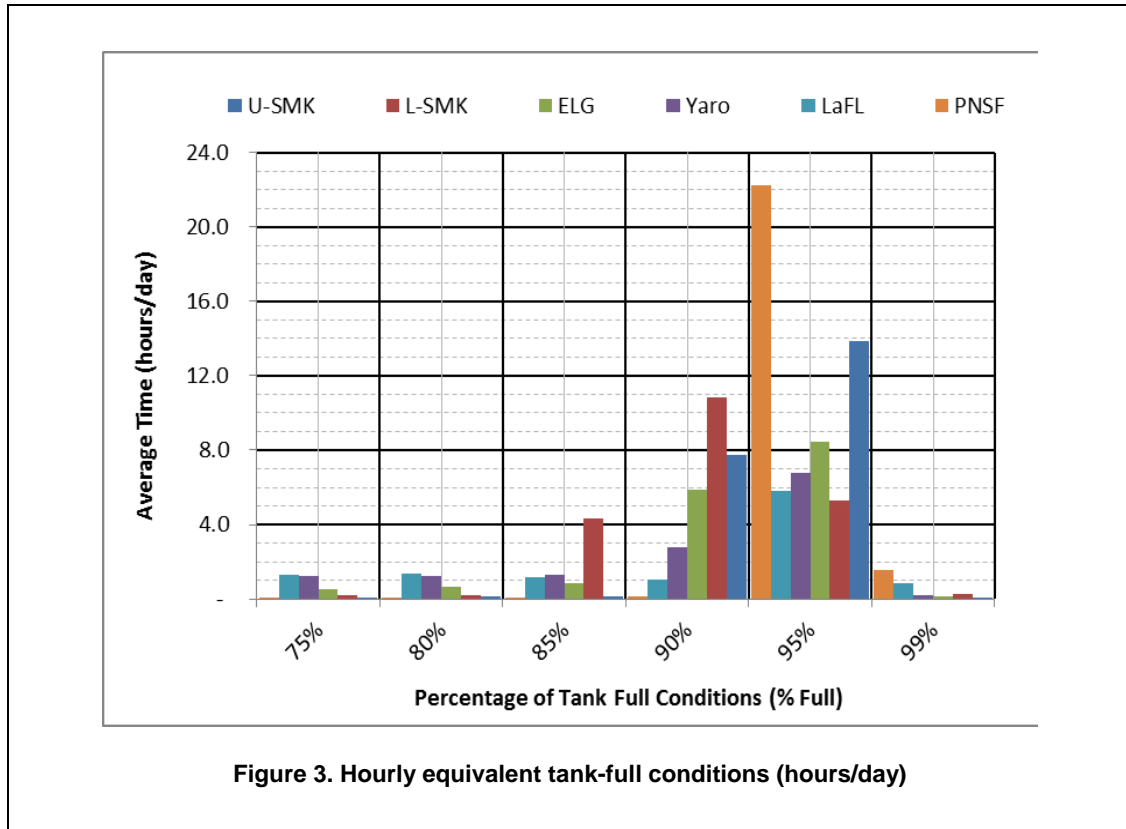
Water quality: The Percent Compliance (water quality score) identifies systems, which are in danger of failing to provide safe drinking water. In this case, all of the systems are delivering relatively clean water and El Guabo is in danger of becoming a failed system. The highest water quality compliance score was located at La Florida, Panama (($\eta_{WQ} = 89.6\%$) where a total of 69 out of 77 tests were conducted from 11 different locations throughout the water system. Whereas, all of the samples studied at this site had a presence of microbial contamination, only two of the samples failed to meet the WHO standard for E.coli and three samples failed the Total Coliform standard. The lowest water quality compliance was located at El Guabo, Nicaragua where a total of 9 samples where collected and 37 of the 49 tests ($\eta_{WQ} = 75.5\%$) were in compliance.

System reliability: The System Reliability score measures the system's ability to provide a continuous supply of safe drinking water and, includes both water quantity and water quality. Using a 70% threshold to

define sustainability; all of the systems are either failing or are in danger of becoming a failed system with the exception of one system. The highest scoring system with respect to overall system performance was at Parque Natural in Panama, which was evaluated with 81.7% efficiency (($\eta_{del} = 100\%$, $\eta_{WQ} = 81.7\%$). The lowest system reliability score ($\eta_{sys} = 40.0\%$) was at La Florida, Panama and both El Guabo and Yaro are failing to continuously deliver both water quantity and water quality.

Table 2. System performance evaluation						
Site Location	**U-SMK**	**L-SMK**	**ELG**	**Yaro**	**LaFL[3]**	**PNSF**
Maximum Level (m)	1.51	1.73	1.36	2.23	2.28	2.20
Minimum Level (m)	0.00	0.00	0.00	0.00	0.00	0.00
Average Level (m)	1.35	1.46	0.98	1.40	1.52	2.14
Median Level (m)	1.44	1.58	1.27	1.80	1.66	2.15
Standard Deviation (m)	0.32	0.41	0.48	0.83	0.67	0.04
Percent Full (PF-75)	91.8	87.9	68.1	56.0	47.7	100
Percent Empty (PE-25)	5.4	6.9	18.8	27.2	10.5	0.0
Water Delivery (η_{del})	**94.6**	**93.1**	**81.2**	**72.8**	**44.8**	**100**
Water Quality Tests (n)	58	58	49	70	77	60
Percent Compliance (η_{WQ})	**79.3**	**79.3**	**75.5**	**84.3**	**89.6**	**81.7**
System Reliability (η_{sys})	**75.0**	**73.8**	**61.3**	**61.4**	**40.0**	**81.7**

Discussion and limitations: Figure 3 shows the upper quartile for all of the water levels studied and is based on percent full values, translated into equivalent hours per day. An investigation of this data reveals that the majority of the water levels studied were within the 85% to 95% tank-full conditions. Whereas this appears to demonstrate that the systems studied are performing well, it is important to note that this research is primarily interested in identifying system failure. As a result, the lower quartile was used to identify a reduction in system performance which ultimately lead to the decision to use the 25% empty criteria when determining system performance where, $\eta_{del} = 1 - PE25$. Limitations with respect to this approach include reporting passing reliability scores where a system is potentially supplying poor quality water. This methodology however provides more information than a pass/fail approach and is more valuable for analytical purposes. Whereas, a pass/fail approach to reporting water quality would identify water treatment needs, it is the opinion of this research group that all community managed water supply systems, should have either household or communal water treatment. Ultimately, a pass/fail evaluation of water quality would result in zero percent compliance and a total system reliability of zero percent which would not meet the primary objective of this research project, which is to investigate correlations between external inputs to the project implementation process and overall system performance; resilience and reliability.

Figure 3. Hourly equivalent tank-full conditions (hours/day)

Conclusions

The sustainability of community managed water supply infrastructure in developing communities is a significant problem, which needs to be more clearly addressed by professionals working in the international development sector. In order to establish relationships between sustainability indicators and the resilience of water delivery systems, principals of reliability engineering should be included in monitoring and evaluation programs to establish metrics for evaluating system performance. This paper presents a methodology to measure the efficiency of water quantity and water quality in order to determine the overall system reliability. Clearly defined metrics for system performance are essential for fully understanding the reasons for system failure and to ensure that development efforts meet the objective of providing sustainable access to safe drinking water.

Additional research is needed to investigate correlations between system performance and external project inputs using the STEEP framework. With respect to water delivery performance, additional research would include household surveys to verify the accuracy of using the PE25 method as a measurement for the efficiency of water delivery systems. In addition to this, establishing a threshold performance-efficiency for defining system failure is recommended. With respect to water quality compliance, detailed field methods for sampling and analysis are recommended to ensure more accuracy and to reduce error propagation. Finally, to investigate the causality of system-failure, a multidisciplinary team is needed. As a result, this study is being presented to open a discussion with WASH sector professionals who are interested in exploring monitoring and evaluation techniques and, to introduce the need for further research and scholarship. WASH sector professionals with an interest in collaborating on performance monitoring are invited to contact the authors of this paper for further discussion.

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Notes

1. ARUP Foresight Consulting originally conceptualized the STEEP Framework in their Driving Change initiative. It is presently being further developed at Villanova University's Graduate Program in Sustainable Engineering and is presented here as an original concept for the WASH sector.
2. An investigation of the water level data for this site would reveal that the water storage facility is continuously overflowing at 2.2-meters.
3. Water Delivery Efficiency (η_{del}) was reduced by 50 percent to account for a scheduled water supply that is available every other day. Further investigation is needed to verify is this is an appropriate approach.
4. Follow up studies are being conducted; contact the authors for more information.

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