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## Research Paper

# Pathways to the successful function and use of mid-tech household water and sanitation systems

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## ABSTRACT

Mid-tech water and sanitation infrastructure – interventions that make moderate use of resources, materials, and technology while providing improvements in health and well-being – may serve an important intermediate role for communities that cannot immediately get high-tech piped infrastructure. However, such systems must be socially appropriate, technically functional, and sustainable. We determined the combinations of technical and social conditions that contribute to the success of household, mid-tech water, sanitation, and hygiene (WASH) systems using qualitative comparative analysis (QCA). We collected data on 32 household mid-tech Portable Alternative Sanitation Systems (PASS) installed in remote, rural Alaskan communities for 1 year. We then coded qualitative and quantitative data for each household 'case' into fuzzy-set values for four technical conditions and four social conditions. We conducted fuzzy-set QCA analyses to determine combinations of conditions (pathways) that led to the successful function and use of PASS. We identified multiple pathways for the success of PASS units, requiring combinations of technical and social conditions. Our analysis reveals that the successful implementation of household mid-tech WASH infrastructure is complicated. We recommend that deliberate steps be taken to engage homeowners, provide appropriate training and support, determine ownership parameters, and ensure the technical sufficiency of mid-tech systems before they are deployed.

**Key words:** Alaska, household, qualitative comparative analysis, sanitation, WASH, water

## HIGHLIGHTS

- Mid-tech water and sanitation infrastructure can be an alternative option for households where piped infrastructure is infeasible.
- Household mid-tech systems require both social and technical considerations to ensure that systems operate correctly and stay in use.
- There are multiple pathways to success that can vary if homes have multiple vulnerability factors.

## INTRODUCTION

Piped water and sewer infrastructure is the gold standard (Overbo *et al.* 2016) for providing 'water and sanitation to all,' as aimed for in the 2030 Sustainable Development Goal for water and sanitation (SDG6). However, piped infrastructure is complex, expensive, resource-intensive, and likely to be unfeasible in many areas in the near future. For example, informal settlements (Mkhize *et al.* 2017), remote rural areas (Edokpayi *et al.* 2018), temporary communities (Mooney 2009), and cold climate regions (Hickel *et al.* 2017) all face high barriers to installing piped water, sanitation, and hygiene (WASH) infrastructure. In these contexts, 'mid-tech' WASH infrastructure may allow communities to achieve water and sanitation access faster than 'high-tech' piped infrastructure without the cost and complexity. 'Mid-tech' WASH infrastructure may also provide significant incremental benefits to health and well-being compared to existing 'low-tech' infrastructure.

While the term 'mid-tech' may be unfamiliar to some, the concept is not. Mid-tech WASH infrastructure represents a range of technologies and can be context-specific. Using a recreational vehicle's demand pump system with water and sewage tanks may be considered mid-tech compared to a piped household. Similarly, a urine-diverting dry toilet inside the home may be considered mid-tech compared to a pit latrine. For the purposes of this paper, we define mid-tech WASH as interventions that offer advancements in WASH practices for health and well-being while making moderate use of resources, materials, innovations, and modern technologies. In this paper, we further confine our scope to household mid-tech infrastructure, which reduces some of the distribution network (e.g. pipe network) challenges that are prevalent in many of the situations where mid-tech infrastructure may be particularly applicable (e.g. temporary settlements, Mooney 2009; cold climate communities, Smith & Low 1996). To address gaps in water and sanitation in challenging environments, mid-tech systems need to be designed that are relatively simple, technically sound, and socially acceptable (Clasen *et al.* 2007; Murphy *et al.* 2009; Eder *et al.* 2015).

In this paper, we evaluate the function and use of one mid-tech WASH system to determine what social and technical factors contribute to the sustainability of household systems over the first year. WASH interventions can have variable outcomes in their operational success and impact on health and well-being (Clasen *et al.* 2007; Starkl *et al.* 2013). In some cases, the technical infrastructure may be sufficient, but there may be social barriers to sustainability (Hueso & Bell 2013; Seymour & Hughes 2014; Mkhize *et al.* 2017; Smiley & Stoler 2020), such as user acceptance or priority addressment (Davis *et al.* 2019a). In other cases, the system may be socially acceptable, but there may be technical challenges that prevent it from serving household needs, such as not sufficiently treating water (Baumgartner *et al.* 2007) or not being fully constructed (Yogananth & Bhatnagar 2018).

In this study, we determined the combinations of social and technical conditions that contributed to the success or failure of one type of mid-tech WASH system, the Portable Alternative Sanitation System (PASS), across 32 households in five communities in rural Alaska. Understanding the inputs and factors that lead to successful household WASH systems can help implementers more efficiently manage projects and improve the outcomes within unserved communities. The installation of PASS units required typical institutional inputs for infrastructure projects, such as capital funding and institutional support (Ashley *et al.* 2008; Kunz *et al.* 2015; Adank *et al.* 2018), and typical technical process steps, such as the creation of engineering plans, and construction according to those plans with appropriate materials (Mihelcic *et al.* 2009; Kaminsky 2015). Additionally, because PASS is a novel mid-tech novel system, social factors like homeowner engagement, enthusiasm for mid-tech, operation and maintenance (O&M) training, ownership, and end-user satisfaction were also hypothesized to impact the success of the systems. We examined the relative necessity and sufficiency (Kaminsky & Jordan 2017) of institutional, technical, and social conditions in leading to the success and failure of PASS units at meeting household WASH needs by conducting a qualitative comparative analysis (QCA) of households. We also evaluated the combinations of conditions that formed pathways for success or failure. These pathways can serve as guidelines to increase the likelihood for sustainability (Andersson *et al.* 2016) of mid-tech household WASH systems in the future.

## METHODS

### Portable alternative sanitation system

The Alaska Native Tribal Health Consortium (ANTHC) developed PASS (Figure 1) in 2014 to provide an alternative mid-tech option for basic water and sanitation to unserved rural households in cold regions. The PASS can be divided into two components: the water component consists of the water treatment system, storage tank, handwash sink, and graywater discharge. The toilet component consists of the urine-diverting dry toilet, urinal, ventilation fan, and urine discharge. Water is self-hauled to the home from treated or natural sources or supplied by a rain catchment system. The PASS water system uses an electric pump to move water through a household treatment system. The treatment system contains a Cryptosporidium-rated cartridge filter and an activated carbon filter, followed by manual chlorination. Treated water is stored in either a 50-gallon or 100-gallon tank that gravity-feeds a single low-flow handwashing sink in the home. The PASS toilet consists of a waterless urinal and urine-diverting dry toilet as an alternative to the typical bucket latrines (honey buckets) or pit latrines (outhouses) used for human waste. Graywater from the sink and separated urine from the toilet and urinal are disposed of in an onsite underground seepage pit. A self-regulating 5-Watt electric heat trace runs down the drain lines to the seepage pit to keep liquid in the line from freezing in winter months (typically September–April). Feces and toilet paper are collected in a bucket inside the toilet, dried with an electric ventilation fan, and disposed of at a landfill or in a burn barrel.

The O&M of PASS was designed to be simple enough that homeowners would be able to maintain the system and do repairs on their own system with minimal expertise and easy-to-access parts and tools. The system was also designed to be adaptable, so homeowners can add features and use it in a way that best reflects their household's needs. For example, in

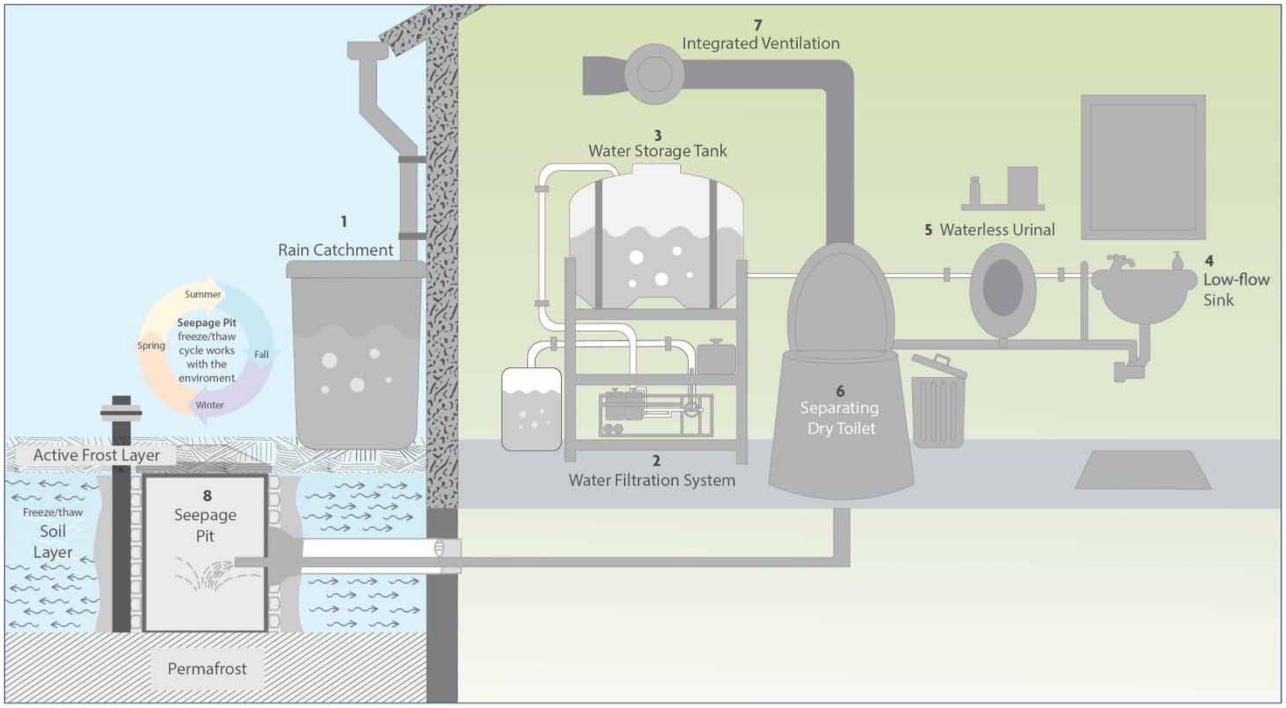



**Figure 1** | A PASS is a household WASH unit developed by the ANTHC in 2015 to provide a mid-tech, adaptable, and portable system for communities without access to piped water and sanitation in their homes.

the event of a freeze-up or clog in the drain lines, the sink and urine drainages can be switched to drain into containers that are manually emptied so that the system can continue to be used during extreme cold weather or blockage. User-centered design concepts were employed during a pilot phase, and subsequent models incorporated a sturdier toilet design, lower barriers to proper O&M, and better adaptability for cold weather. For example, the toilet can be changed from a urine-diverting dry toilet to a bucket latrine with ventilation ('vented honey bucket') by removing the separating piece. The conversion option allows households that are physically uncomfortable using the separator seat to use the ventilated toilet in a modified way that they may be more comfortable with.

Additional supporting community infrastructure facilitates the use of PASS. Although PASS can treat natural water sources to drinking water quality standards (US Environmental Protection Agency 2009), a centralized watering point can further improve access and decrease time for households to haul water to their homes. For example, a community laundry and shower facility (called a 'washeteria' in rural Alaska) can provide access to hygiene activities that would otherwise require large quantities of water hauled to the home (Eichelberger *et al.* 2020). Communities need a landfill that is lined and permitted to receive dry human waste, and households need a mode of transportation to haul water to and waste from the home.

To date, PASS units have been implemented in six rural Alaska communities over 6 years as part of a research and development project, but they are still considered an experimental and novel system. This study uses QCA, a case-oriented, configurational, comparative method to determine the combinations of conditions that have contributed to the success or failure of PASS units. These combinations can provide insight into improving PASS technology and implementation and provide understanding as to what is needed to make mid-tech systems work for household WASH.

## Installation and data collection

PASS units were installed in 37 volunteer households in five remote, rural, and unpiped Alaska Native communities between 2015 and 2019. After each year, PASS designers reevaluated the systems and made some changes to the design, materials, or layout of the system based on end-user feedback. Thirty-two households gave written consent for their data to be used for this research. Each household is treated as a case in the analyses presented here. Communities were invited to participate in the PASS pilot program if they were working with ANTHC on water and sanitation projects but did not have plans or funding for providing piped services to households. Households were selected through tribal government recommendations and individual requests to participate. Households were then evaluated by engineering and survey teams to ensure adequate space in and around the home and the structural integrity of the building before receiving the PASS units.

Household members who were knowledgeable about household water and sanitation practices were interviewed before installation of PASS to determine their motivation for getting PASS, expectations for the system, technical capacity for O&M, and to document household characteristics, such as number of occupants, age composition, and vehicle access. Individual engineering designs for each home were developed by professional engineers. The systems were installed by ANTHC certified journeymen plumbers and electricians along with construction technicians from the local communities. In some cases, privately contracted construction workers were hired to lead the work with the assistance of local technicians, including PASS homeowners. All systems were covered by a 1-year warranty on parts and installation.

Training on O&M was conducted with individual homeowners by ANTHC staff. Project staff then followed up with households by phone or in person every 1–3 months for at least 1 year after installation of the systems to conduct a semi-structured interview about the system. Adults in the household were asked about the operation and use of their system, whether routine O&M activities were being performed, whether they were having challenges, and how challenges were being resolved. When possible, interview responses about the function and use of systems were corroborated with visual inspections and observations. If households needed additional training or warranty maintenance, it was provided at the time of the interview or as soon as parts and labor were available (usually within 3 months). ANTHC project staff (including author Mattos) conducted follow-up phone calls and visits with community leaders and individual homeowners for 1–3 years after installation of the systems. We collected information about community landfills, hauling systems, and washeteria availability and functionality during site visits at least twice in each community during the first year that PASS units were in operation to understand community infrastructure access for all homes. Thus, extensive case knowledge based on these collected data can be compiled for each household.

### Qualitative comparative analysis

QCA was used to evaluate PASS outcomes. QCA is a configurational comparative method that bridges the strengths of case-oriented and variable-oriented approaches. It examines individual cases in detail to understand social phenomena while revealing cross-case patterns that describe underlying structures and relationships that persist outside of individual cases. QCA requires in-depth case knowledge and uses set theory to assess relationships between factors and outcomes. It allows for the analysis of causal complexity to identify different combinations of causal conditions that lead to specific outcomes – in this case the 'success' or 'failure' of PASS units, defined as function, use, and acceptance. QCA was appropriate for this analysis because there were an intermediate number of household 'cases' ($N = 32$) that loaned themselves to be evaluated more effectively with QCA than with a statistical (large N) or case study (small N) method (Ragin 1987). Furthermore, we expected multiple conditions to contribute to particular outcomes and for different pathways to lead to 'success' than to 'failure' (Ragin 2006).

### Selection of conditions and outcomes

Qualitative data from interviews, inspections, observations, technical assistance logs, and community infrastructure evaluations were coded for conditions that could contribute to the success or failure of PASS using both deductive and inductive methods. In deductive coding, we developed a list of initial conditions from published literature, government reports, and professional experience to build a theory of relevant conditions. Then, we documented case details in spreadsheets and inductively coded the data into the initial conditions, while searching the data for additional conditions that had not yet been identified. For example, community access to resources, ongoing external support for O&M, and adequate technical training and knowledge were all identified from the literature as being important aspects of O&M (Brikké *et al.* 2003; Ashley *et al.* 2008; Kaminsky & Javernick-Will 2012; Chatterley *et al.* 2014; Tilley *et al.* 2014; Opdyke *et al.* 2018). From the examination of our case data, we also found that household access to resources (such as having a person in the home who could haul water and waste) and access to vehicles were also important aspects of O&M. We compiled case data for all identified conditions.

Next, we identified and removed domain conditions (conditions that do not vary between the cases) from the analysis. Domain conditions included low levels of tribal support and advocacy, external funding for systems, costs of O&M, absence of hygiene education, community participation, presence of extreme weather and climatic conditions, similar quality materials and pre-fabricated kits, appropriate conditions for seepage, and maintenance complexity. We removed other conditions from the analysis if there was insufficient information for all of the cases, including household socioeconomic status and education attained (see Supplementary data). Finally, we reviewed and refined the definitions of each condition to remove redundant concepts and link sub-conditions into macroconditions (see Supplementary data). We ultimately chose eight conditions to consider in this analysis, covering both technical and social considerations, as defined below (additional detail on choosing conditions, definitions, calibration, and robustness tests is available in Supplementary Material, Table S1 and Figure S2).

### Technical conditions

- *Technical sufficiency*: appropriate engineering planning and design, and high-quality construction.
- *Major technical problem*: major technical problems or barriers that would challenge the system's function or use or require significant troubleshooting and homeowner investment to fix.
- *O&M*: access to resources, support, and capacity for O&M and routine performance of preventative maintenance.
- *Supporting community infrastructure*: reliable access to a functioning washeteria, adequate waste disposal facilities, and a reliable watering point.

### Social conditions

- *Vulnerability*: the presence of characteristics that may contribute to additional daily challenges related to having no convenient WASH infrastructure in the home. Households were characterized as vulnerable if they had very young children, elders, or residents with disabilities in the home. Vulnerability was hypothesized to either contribute to the success of PASS because the household had a high need for the system, or to failure of PASS because the household may have had barriers to using and keeping it functioning. Vulnerability is considered to be a transient characteristic of households (e.g. vulnerability will change as children grow into adults or when a resident recovers from a temporary disability). Vulnerability is thus considered here in order to identify whether vulnerable households may need different support or additional considerations to contribute to the success of PASS units.
- *Enthusiasm*: self-reported household excitement about the PASS before installation.
- *Ownership*: installing agency providing formal transfer of ownership and homeowner accepting ownership of the unit, as shown by the performance of modifications and troubleshooting on their own.
- *User satisfaction*: the system meeting household needs and expectations for water and sanitation services.

We defined the outcome of PASS 'success' as 'in use and technically functional at point in time 12 months after installation' based on several WASH QCA studies that indicated that function and use were both important in the determination of whether WASH interventions were fulfilling their intended goals (Kaminsky & Javernick-Will 2012; Kaminsky 2015; Marks *et al.* 2018; Davis *et al.* 2019b). The use of PASS in conjunction with other WASH infrastructure in the home (e.g. other water storage containers or pit latrines) was still considered to be success. The outcome of 'not success' (i.e. failure) was also analyzed using Boolean mathematics: $\sim A = (1 - A)$, where the '$\sim$' symbol means 'not' (Ragin 2008b).

## Calibration

We used indirect calibration to structure levels within each variable using case knowledge and theory (Schneider & Wagemann 2010; Basurto & Speer 2012). We defined the condition and set anchor points for fully in-set (fuzzy-set score of 1), fully out-of-set (fuzzy-set score of 0), and the crossover point (fuzzy-set score of 0.5) based on theory. Then, we examined the data to determine where natural gaps or meaningful differences between cases existed (Davis *et al.* 2019b). For example, 'vulnerability' included three sub-conditions: presence of at least one child under 5 years of age or at least one elder, more than twice as many children as adults, or injury or disability. Almost every home had at least one vulnerability characteristic, but far fewer had more than two, and there appeared to be a significant difference in the way that households conducted their daily activities between houses with less than two characteristics compared to houses with two or more characteristics. We therefore calibrated the dataset so that a score of '0' was given to all homes with zero or one vulnerability sub-condition and a score of '1' to all homes with two or three sub-conditions. For five conditions (O&M, ownership, community infrastructure, technical sufficiency, and user satisfaction), a four-value set was used with scores corresponding to fully in the set (1), more in than out (0.67), more out than in (0.33), and fully out (0). For three conditions (enthusiasm, vulnerability, and major problem), there was a single natural breaking point between the character of cases, so a two-value crisp-set was used (1 for full in-set and 0 for fully out-of-set, see Supplementary Material, Table S2 for calibration dictionary).

Outcomes were coded using qualitative scales and logical formulas to combine multiple parameters. Based on interviews and case knowledge, each case was assigned a grade of low, medium, or high for function and for use for both the toilet component and the water component of PASS. The minimum value between function and use was used to order the cases, and then cases were qualitatively calibrated into a four-value set based on natural breaks and case knowledge. To determine overall PASS unit function and use, the scores for the toilet and the water components were averaged and then qualitatively calibrated into a six-value set based on case knowledge. The identification of conditions and outcomes, coding of data, and calibration were all done iteratively to ensure that all important aspects of case data were captured without redundancy. Iteration also allowed us to examine the cases that shared each score for each factor and evaluate whether there were uncaptured differences between the groups.

### Analysis

After assigning membership scores to each case for each condition and outcome, we used the fsQCA 2.0 software (Ragin 2008a) to compile the truth table and conduct the analysis. The goal of the analysis was to identify 'pathways,' or combinations of conditions that were common to households with the same outcome. We used a frequency score of 1.0 case and a consistency threshold of 0.8 for all analyses (Ragin 2008a). We assessed solution pathways using consistency and coverage. Consistency is a measure of how well the cases that share a given combination of conditions agree in the outcome (measured from 0 to 1). Coverage is a measure of how much of the outcome is explained by the individual solution terms and the entire pathway (measured from 0 to 1). Coverage measures how much of the outcome a particular combination of conditions accounts for. Consistency and coverage can be calculated as follows:

$X_i$: a particular case's membership in a condition or set of conditions ('pathway').
$Y_i$: a particular case's membership in the outcome.
$\text{Consistency} = \Sigma[\min(X_i, Y_i)]/\Sigma(X_i)$.
$\text{Coverage} = \Sigma[\min(X_i, Y_i)]/\Sigma(Y_i)$.

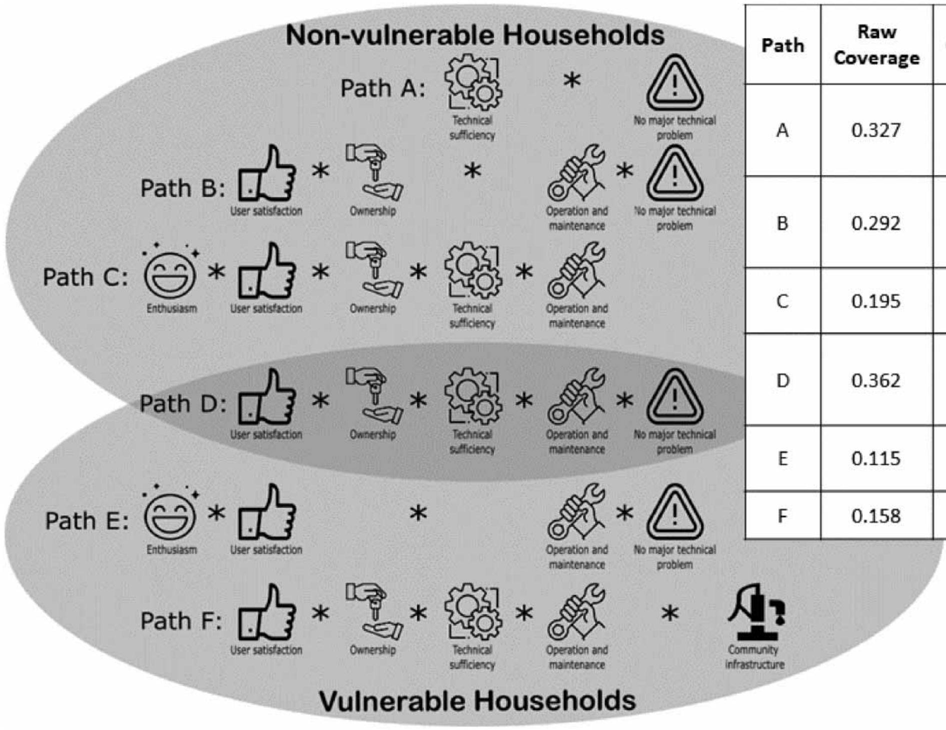
Coverage is partitioned into raw coverage and unique coverage for each solution to demonstrate the degree of equifinality present in the solutions and to represent the relative weight of each solution to explain the variability of the cases (Ragin 2006). To reduce the number of possible solutions, we made assumptions about the direction of the effect that each condition would have on the outcome for all conditions except one (Supplementary Material, Table S1). We assumed that the presence of enthusiasm, O&M, community infrastructure, ownership, user satisfaction, and technical sufficiency would lead to success. We assumed that the absence of a problem would lead to success. For vulnerability, we made no directional assumption (as described above). These assumptions contributed to the development of intermediate solutions, which we discuss below. We also assessed the necessity of each individual condition. Conditions were considered to be necessary if they had an individual consistency of 0.9 or greater and an individual coverage of 0.5 or greater (Legewie 2013).

## RESULTS AND DISCUSSION

### Pathways to the success of PASS

Out of 32 household PASS units observed as cases for this study, 20 (63%) had an outcome of 'success' (an outcome score of >0.5). Successful systems had a range of outcomes. Some were working well but were only partially in use because of homeowner habits and preferences. For example, in Case 31, the elder resident of the home preferred to use their older water buckets than to fill the PASS water tank. Other successful homes had minor functional challenges. For example, Case 7 had their drain lines freeze, but they were able to make modifications to their unit to keep it working. In other successful cases, such as Case 10, homes completely replaced their prior water storage containers and bucket latrines and fully adopted the system.

No individual condition reached a necessity score greater than 0.9 for the PASS success outcome, but all eight contributing conditions that were included in the analysis appeared at least once in various pathways that led to the success of PASS units at the end of their first year after installation. Six pathways of three to six conditions each were identified that lead to success (Figure 2), with a total solution coverage of 0.69 and consistency of 0.93, describing 16 unique cases. Every pathway required general technical sufficiency and/or the absence of a major technical problem for success. Five of the six pathways also




| Path | Raw Coverage | Consist. | Case IDs |
|---|---|---|---|
| A | 0.327 | 0.926 | 8, 3, 27, 2, 10, 30 |
| B | 0.292 | 0.971 | 17, 15, 20, 2, 10, 30 |
| C | 0.195 | 1.00 | 13, 2, 10, 30 |
| D | 0.362 | 0.932 | 11, 5, 12, 2, 10, 30 |
| E | 0.115 | 0.929 | 12, 14, 26 |
| F | 0.158 | 0.900 | 25 |

**Figure 2** | Pathways to the success of PASS units are complex and require technical considerations (such as general technical sufficiency, O&M, and community infrastructure) and social considerations (such as end-user enthusiasm, user satisfaction, and ownership). Non-vulnerable and vulnerable households had slightly different pathways for success, and thus may need to be engaged differently to ensure the success of the mid-tech household WASH systems.

required the conditions O&M and user satisfaction, and the same five required the conditions enthusiasm and/or ownership as well. Pathways differed slightly between households with and without vulnerability characteristics (Figure 2).

Path A is the simplest combination, requiring a lack of vulnerability, technical sufficiency, and no major problem. Six cases followed this path, which suggests that for non-vulnerable homes, it is possible to achieve success with simple technical inputs and without major social inputs. The six cases that followed Path B were satisfied with the system, took care of any challenges, and had the resources to do so. These cases were successful whether or not they had community infrastructure, technical sufficiency, or were excited about the system before it was installed. Path C represents four homes with high enthusiasm for the system and technical sufficiency of the system, along with lack of vulnerability, ownership, O&M, and user satisfaction. These homes showed motivation to make sure that the system worked if they had technical problems.

Path E and F show sufficient combinations for vulnerable households. Path E represents three homes that had high enthusiasm for the system, no major technical problems, user satisfaction, and O&M. Each of these homes had strong heads of household who were advocates of the system and seemed to make a point of finding help to keep the system running when needed. One home followed Path F, which was the only pathway that required community infrastructure for success, along with technical sufficiency, ownership, user satisfaction, and O&M.

Path D is the only pathway that can apply to vulnerable or non-vulnerable homes and requires technical sufficiency, no major problem, ownership, user satisfaction, and O&M. Six homes followed this pathway. Path D was the only pathway that required the presence of all three household technical conditions: technical sufficiency, no major problem, and O&M. This may imply that with extremely high-quality technical infrastructure, social considerations are less critical, though not unimportant. For a system to be successful, users still have to be satisfied with the system and feel a sense of ownership to ensure that it works and meets their needs. The pathways to failure are discussed in the Supplementary data.

Overall, the pathways for the success of PASS are complex, requiring multiple inputs from the individual households and from the institution promoting and running the project. There is one short pathway (Path A) for non-vulnerable homes where technical considerations alone are sufficient. However, the majority of the pathways to success require a combination of social inputs, such as enthusiasm for the system, user satisfaction with what is built, and/or ownership of the system. Notably, most required conditions were at the individual household level. For example, community infrastructure only appeared in one pathway. Therefore, focusing on community inputs seems to be less important for PASS success, as defined here, than focusing on ensuring solid technical operation and engagement at the household level. WASH practitioners who are deploying mid-tech household systems may see increased success if they are able to (1) engage homeowners about the ways WASH infrastructure can improve health and well-being (to promote enthusiasm and user satisfaction), (2) ensure high technical quality of the systems (to confirm technical sufficiency and the absence of major technical problems), and (3) build capacity for O&M and ownership.

In general, the positive state of each condition (e.g. enthusiasm and user satisfaction) contributed to the success of PASS, and the negative state of each condition (e.g. the absence of enthusiasm and ownership, or the presence of a major problem) contributed to failure. This was not true for community infrastructure though. The presence of community infrastructure was expected to be supportive of PASS success (based on the assumptions laid out in Supplementary Material, Table S1) because it would increase the ease and benefits of using PASS. However, this condition only appeared in one pathway to success, and both the presence and absence of community infrastructure led to failure in different pathways. This may be attributable to the fact that PASS is a mid-tech solution to water and sanitation challenges, representing a step-up from bucket latrines and water jugs that falls short of 'limitless' piped water and flush toilets. Because it is not a fully piped system, PASS may not provide people with the full range of services that they want. Therefore, some households (such as Cases 28 and 23) that have access to other community infrastructure for their water and sanitation needs (such as a reliable washeteria where they can access water and a safe disposal method for human waste) may decide to use that community infrastructure instead of using their PASS unit. Although our analyses did not find the presence of community infrastructure to contribute to the success of PASS units in most cases, community infrastructure has been shown to be an important component in WASH systems in other studies (Howard & Bartram 2003; Thomas *et al.* 2013; Raczniak *et al.* 2016). In general, community infrastructure that served complementary needs should be considered and enhanced alongside the provision of individual household systems.

### Limitations

We did not have sufficient information on some conditions that were hypothesized to impact the outcome, such as socio-economic status or education. We also had limited diversity on some institutional and financial aspects of this system, such as local and regional support for mid-tech systems, external funding for systems, and behavior change education. These factors have been shown to impact the outcomes of WASH infrastructure in other studies (Chatterley *et al.* 2013; Barstow *et al.* 2014; Marks *et al.* 2018), thus may be important for mid-tech WASH systems too. The scope of this study was limited by its number of household cases ($N = 32$), which is small for establishing trends and commonalities between households but relatively large for a QCA study (Marks *et al.* 2018; Peletz *et al.* 2018). Households in all communities were invited to volunteer to receive PASS units and to participate in the study, but there may have been significant implicit differences between households that joined the study and those that declined it and who are therefore not captured in the data presented here. For example, volunteer households may be more excited about WASH infrastructure options or may have been more open to discussing and troubleshooting challenges with their systems than the homes that opted out of the study. Furthermore, we relied heavily on interview data (supplemented with technical inspections and observations) to determine social conditions, such as enthusiasm or user satisfaction, which required a level of rapport between the interviewer and interviewee to get accurate information. The scope of this paper did not allow us to look at the driving factors behind some of the social conditions that we considered here (e.g. what led to attitudes of satisfaction or presence of vulnerability characteristics, as in Daniel *et al.* 2019), which is an important direction for future research to examine. Finally, the data presented here have evaluated PASS units after a limited follow-up period of 1 year, but continued data collection over 2 or more years (MacMahon & Gill 2018) may yield different outcomes and valuable new insights.

### Significance of findings

All of the pathways showed a complex combination of factors that are required for mid-tech household water and sanitation units to be successful. QCA sometimes reveals simplified pathways paving the way toward success based on combinations of a few of hypothesized conditions (e.g. Chatterley *et al.* 2014; Davis *et al.* 2019b). However, for PASS units, many different types of inputs were needed for success, and many of those inputs require the effort of or engagement with homeowners. This may differ from high-tech WASH infrastructure (such as centralized piped systems), where municipalities or private companies are responsible for the funding, technical sufficiency, and preventing problems, and certified operators are responsible for O&M, leaving less responsibility to individual homeowners. Well-known interventions, like flush toilets and running water, are also likely to bring enthusiasm and user satisfaction in homes receiving first-time service. Mid-tech systems that provide incremental benefits may represent disappointment for homes that want a high-tech system with fewer homeowner responsibilities, even if mid-tech systems improve health and well-being. However, the relatively simple technical components of mid-tech infrastructure like PASS are likely to be significantly easier for homeowners to adopt compared to household-scale high-tech systems.

Ownership was found to be an important condition for success and the lack of ownership lead to the failure of PASS units, which has commonly been reported to be a factor in both low-tech (Rodgers *et al.* 2007; Kaminsky & Javernick-Will 2012) and high-tech (Najm *et al.* 2017) WASH infrastructure as well. If users feel ownership over the infrastructure, they may be more likely to maintain it, find assistance when needed, or adapt the system to ensure that it meets their specific needs, which relates to the O&M condition. Where ownership is lacking, users might not feel like the system addresses their priorities and may not feel agency to modify, troubleshoot, or fix the system (impacting O&M and user satisfaction conditions). In centralized systems, different types of ownership arrangements are possible (e.g. private, public, public–private partnerships), and thinking about ownership and management early on is critical (Marks & Davis 2012; Chowns 2015). Future research should look into mimicking this approach to improve the sense of ownership of household systems, too, so that roles and responsibilities can be clear from the beginning.

The specific ways that implementers need to engage and build social acceptance of PASS may differ based on whether the households have multiple vulnerability factors. For example, households with elders or physical disabilities may require additional assistance to ensure the success of PASS, such as external support for O&M (as shown in Path E), aid with hauling water and waste, or help accessing community infrastructure (as shown in Path C). Many WASH professionals (e.g. Eichelberger 2010; Gero *et al.* 2014; Hoque *et al.* 2019; Anthonj *et al.* 2020) have documented major differences in access to resources for vulnerable populations that have impacted their ability to get water and sanitation services, and factors such as mental and physical health are known to be related to water security (Smiley & Stoler 2020). With over a million people in the United States who do not yet have access to water and sanitation, many of which are in historically marginalized and vulnerable communities (Riggs *et al.* 2017), all practitioners must prioritize the development of specific approaches to achieve access to WASH for vulnerable households.

Pathways for the success of mid-tech PASS units revealed that multiple technical and social factors were found to be important. This suggests that a system that is *only* technically sound may still be unsuccessful at meeting household water and sanitation needs without efforts to ensure that users are enthusiastic about the system, take ownership of the system, and are completely satisfied by the utility of the system. Mid-tech systems will, by definition, provide different capabilities than high-tech WASH infrastructure. However, homeowners must feel like mid-tech infrastructure provides a significant improvement over existing low-tech infrastructure in order for novel mid-tech to be successful. Furthermore, engaging communities and households in the infrastructure process and building excitement for the system will not lead to success if the system is not also functioning well in a technical capacity. If mid-tech PASS units continue to be pursued as a solution to fill household water and sanitation needs, implementers must ensure that the units are technically sound and that the household is prepared to accept and use the system.

The idea that 'access to WASH is no longer up to engineers alone' (Mara *et al.* 2010; Tilley *et al.* 2014; Mihelcic *et al.* 2017) has been increasingly acknowledged in WASH engineering for over a decade. For mid-tech WASH systems, engineers must continue to produce solid technical infrastructure while collaborating with communities, households, and other experts to ensure social acceptance and long-term sustainability.

## CONCLUSION

Household mid-tech WASH infrastructure may be important for improving health and well-being in communities that cannot immediately gain access to piped water and sanitation services. Determining how to implement successful mid-tech infrastructure systems can improve coverage of WASH services without compromising environmental or economic sustainability. We identified complex pathways of multiple technical and social conditions that must be present for the success of one type of mid-tech WASH system (PASS). This analysis reveals that household success and failure are heterogeneous and complicated. Groups promoting household mid-tech WASH infrastructure must recognize that households are unique and may require different types of inputs and engagement from practitioners to ensure the success of interventions. We recommend that deliberate steps be taken to engage homeowners, provide appropriate training and support, determine ownership parameters, and ensure the technical sufficiency of mid-tech systems before they are deployed. Importantly, integrating the concept of 'mid-tech' infrastructure into the WASH sector requires that we acknowledge a continuum of technologies that can provide service to households that lack their desired level of WASH access. Future research in engineering and public health can innovate in this new space to propose targeted solutions for unique and challenging environments.

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## DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

## REFERENCES

Adank, M., Godfrey, S., Butterworth, J. & Defere, E. 2018 Small town water services sustainability checks: development and application in Ethiopia. *Water Policy* **20** (S1), 52–68. https://doi.org/10.2166/wp.2018.004.

Andersson, K., Dickin, S. & Rosemarin, A. 2016 Towards 'sustainable' sanitation: challenges and opportunities in urban areas. *Sustainability* **8** (12), 1289. https://doi.org/10.3390/su8121289.

Anthonj, C., Setty, K. E., Ezbakhe, F., Manga, M. & Hoeser, C. 2020 A systematic review of water, sanitation and hygiene among Roma communities in Europe: situation analysis, cultural context, and obstacles to improvement. *International Journal of Hygiene and Environmental Health* **226**, 113506. https://doi.org/10.1016/j.ijheh.2020.113506.

Ashley, R., Blackwood, D., Butler, D., Jowitt, P., Davies, J., Smith, H., Gilmour, D. & Oltean-Dumbrava, C. 2008 Making asset investment decisions for wastewater systems that include sustainability. *Journal of Environmental Engineering* **134** (3), 200–209. https://doi.org/10.1061/(ASCE)0733-9372(2008)134:3(200).

Barstow, C. K., Ngabo, F., Rosa, G., Majorin, F., Boisson, S., Clasen, T. & Thomas, E. A. 2014 Designing and piloting a program to provide water filters and improved cookstoves in Rwanda. *PLoS ONE* **9** (3), e92403. https://doi.org/10.1371/journal.pone.0092403.

Basurto, X. & Speer, J. 2012 Structuring the calibration of qualitative data as sets for qualitative comparative analysis (QCA). *Field Methods* **24** (2), 155–174. https://doi.org/10.1177/1525822X11433998.

Baumgartner, J., Murcott, S. & Ezzati, M. 2007 Reconsidering 'appropriate technology': the effects of operating conditions on the bacterial removal performance of two household drinking-water filter systems. *Environmental Research Letters* **2** (2), 024003. https://doi.org/10.1088/1748-9326/2/2/024003.

Brikké, F., Bredero, M., Supply, W. & Network, M. 2003 *Linking Technology Choice with Operation and Maintenance in the Context of Community Water Supply and Sanitation: A Reference Document for Planners and Project Staff*.

Chatterley, C., Linden, K. G. & Javernick-Will, A. 2013 Identifying pathways to continued maintenance of school sanitation in Belize. *Journal of Water, Sanitation and Hygiene for Development* **3** (3), 411. https://doi.org/10.2166/washdev.2013.128.

Chatterley, C., Javernick-Will, A., Linden, K. G., Alam, K., Bottinelli, L. & Venkatesh, M. 2014 A qualitative comparative analysis of well-managed school sanitation in Bangladesh. *BMC Public Health* **14** (1), 6.

Chowns, E. 2015 Is community management an efficient and effective model of public service delivery? Lessons from the rural water supply sector in Malawi: is community management efficient and effective? *Public Administration and Development* **35** (4), 263–276. https://doi.org/10.1002/pad.1737.

Clasen, T., Schmidt, W.-P., Rabie, T., Roberts, I. & Cairncross, S. 2007 Interventions to improve water quality for preventing diarrhoea: systematic review and meta-analysis. *BMJ* **334** (7597), 782. https://doi.org/10.1136/bmj.39118.489931.BE.

Daniel, D., Diener, A., Pande, S., Jansen, S., Marks, S., Meierhofer, R., Bhatta, M. & Rietveld, L. 2019 Understanding the effect of socio-economic characteristics and psychosocial factors on household water treatment practices in rural Nepal using Bayesian belief networks. *International Journal of Hygiene and Environmental Health*. https://doi.org/10.1016/j.ijheh.2019.04.005

Davis, A., Javernick-Will, A. & Cook, S. M. 2019a Priority addressment protocol: understanding the ability and potential of sanitation systems to address priorities. *Environmental Science & Technology* **53** (1), 401–411. https://doi.org/10.1021/acs.est.8b04761.

Davis, A., Javernick-Will, A. & Cook, S. M. 2019b The use of qualitative comparative analysis to identify pathways to successful and failed sanitation systems. *Science of the Total Environment* **663**, 507–517. https://doi.org/10.1016/j.scitotenv.2019.01.291.

Eder, J. M., Mutsaerts, C. F. & Sriwannawit, P. 2015 Mini-grids and renewable energy in rural Africa: how diffusion theory explains adoption of electricity in Uganda. *Energy Research & Social Science* **5**, 45–54. https://doi.org/10.1016/j.erss.2014.12.014.

Edokpayi, J., Rogawski, E., Kahler, D., Hill, C., Reynolds, C., Nyathi, E., Smith, J., Odiyo, J., Samie, A., Bessong, P. & Dillingham, R. 2018 Challenges to sustainable safe drinking water: a case study of water quality and use across seasons in rural communities in Limpopo Province, South Africa. *Water* **10** (2), 159. https://doi.org/10.3390/w10020159.

Eichelberger, L. P. 2010 Living in utility scarcity: energy and water insecurity in Northwest Alaska. *American Journal of Public Health* **100** (6), 1010–1018.

Eichelberger, L., Hickel, K. & Thomas, T. K. 2020 A community approach to promote household water security: combining centralized and decentralized access in remote Alaskan communities. *Water Security* **10**, 100066. https://doi.org/10.1016/j.wasec.2020.100066.

Gero, A., Carrard, N., Murta, J. & Willetts, J. 2014 Private and social enterprise roles in water, sanitation and hygiene for the poor: a systematic review. *Journal of Water, Sanitation and Hygiene for Development* **4** (3), 331–345. https://doi.org/10.2166/washdev.2014.003.

Hickel, K. A., Dotson, A., Thomas, T. K., Heavener, M., Hebert, J. & Warren, J. A. 2017 The search for an alternative to piped water and sewer systems in the Alaskan Arctic. *Environmental Science and Pollution Research* **25**, 32873–32880.

Hoque, S. F., Hope, R., Arif, S. T., Akhter, T., Naz, M. & Salehin, M. 2019 A social-ecological analysis of drinking water risks in coastal Bangladesh. *Science of the Total Environment* **679**, 23–34. https://doi.org/10.1016/j.scitotenv.2019.04.359.

Howard, G. & Bartram, J. 2003 *Domestic Water Quantity, Service Level and Health*. World Health Organization, Geneva.

Hueso, A. & Bell, B. 2013 An untold story of policy failure: the Total Sanitation Campaign in India. *Water Policy* **15** (6), 1001–1017. https://doi.org/10.2166/wp.2013.032.

Kaminsky, J. 2015 The fourth pillar of infrastructure sustainability: tailoring civil infrastructure to social context. *Construction Management and Economics* **33** (4), 299–309. https://doi.org/10.1080/01446193.2015.1050425.

Kaminsky, J. & Javernick-Will, A. 2012 Causes for sustainable maintenance and operation of on-site sanitation systems. In: *Construction Research Congress 2012*.

Kaminsky, J. & Jordan, E. 2017 Qualitative comparative analysis for WASH research and practice. *Journal of Water Sanitation and Hygiene for Development* **7** (2), 196–208. https://doi.org/10.2166/washdev.2017.240.

Kunz, N. C., Fischer, M., Ingold, K. & Hering, J. G. 2015 Why do some water utilities recycle more than others? A qualitative comparative analysis in New South Wales, Australia. *Environmental Science & Technology* **49** (14), 8287–8296. https://doi.org/10.1021/acs.est.5b01827.

Legewie, N. 2013 An introduction to applied data analysis with qualitative comparative analysis. *Forum Qualitative Sozialforschung/Forum: Qualitative Social Research* **14** (3), Article 3. https://doi.org/10.17169/fqs-14.3.1961.

MacMahon, J. & Gill, L. W. 2018 Sustainability of novel water treatment technologies in developing countries: lessons learned from research trials on a pilot continuous flow solar water disinfection system in rural Kenya. *Development Engineering* **3**, 47–59. https://doi.org/10.1016/j.deveng.2018.01.003.

Mara, D., Lane, J., Scott, B. & Trouba, D. 2010 Sanitation and health. *PLoS Medicine* **7** (11), e1000363. https://doi.org/10.1371/journal.pmed.1000363.

Marks, S. J. & Davis, J. 2012 Does user participation lead to sense of ownership for rural water systems? Evidence from Kenya. *World Development* **40** (8), 1569–1576. https://doi.org/10.1016/j.worlddev.2012.03.011.

Marks, S., Kumpel, E., Guo, J., Bartram, J. & Davis, J. 2018 Pathways to sustainability: a fuzzy-set qualitative comparative analysis of rural water supply programs. *Journal of Cleaner Production* **205**. https://doi.org/10.1016/j.jclepro.2018.09.029

Mihelcic, J. R., Fry, L. M., Myre, E. A., Phillips, L. D., Barkdoll, B. D. & Carter, J. 2009 *Field Guide to Environmental Engineering for Development Workers: Water, Sanitation, and Indoor Air*, 1st edn. American Society of Civil Engineers Press, Reston, VA.

Mihelcic, J. R., Naughton, C. C., Verbyla, M. E., Zhang, Q., Schweitzer, R. W., Oakley, S. M., Wells, E. C. & Whiteford, L. M. 2017 The grandest challenge of all: the role of environmental engineering to achieve sustainability in the world's developing regions. *Environmental Engineering Science* **34** (1), 16–41.

Mkhize, N., Taylor, M., Udert, K. M., Gounden, T. G. & Buckley, C. A. 2017 Urine diversion dry toilets in eThekwini Municipality, South Africa: acceptance, use and maintenance through users' eyes. *Journal of Water, Sanitation and Hygiene for Development* **7** (1), 111–120. https://doi.org/10.2166/washdev.2017.079.

Mooney, E. 2009 When 'temporary' lasts too long. *Forced Migration Review* **33**, 64–66.

Murphy, H. M., McBean, E. A. & Farahbakhsh, K. 2009 Appropriate technology – a comprehensive approach for water and sanitation in the developing world. *Technology in Society* **31** (2), 158–167. https://doi.org/10.1016/j.techsoc.2009.03.010.

Najm, M. A., Hasan, H., Alameddine, I. & El-fadel, M. 2017 Onsite graywater reclamation towards alleviating water shortages at the household level. *Water and Society* **216**, 87–99.

Opdyke, A., Javernick-Will, A. & Koschmann, M. 2018 A comparative analysis of coordination, participation, and training in post-disaster shelter projects. *Sustainability* **10** (11), 4241. https://doi.org/10.3390/su10114241.

Overbo, A., Williams, A. R., Evans, B., Hunter, P. R. & Bartram, J. 2016 On-plot drinking water supplies and health: a systematic review. *International Journal of Hygiene and Environmental Health* **219** (4), 317–330. https://doi.org/10.1016/j.ijheh.2016.04.008.

Peletz, R., Kisiangani, J., Bonham, M., Ronoh, P., Delaire, C., Kumpel, E., Marks, S. & Khush, R. 2018 Why do water quality monitoring programs succeed or fail? A qualitative comparative analysis of regulated testing systems in sub-Saharan Africa. *International Journal of Hygiene and Environmental Health* **221** (6), 907–920. https://doi.org/10.1016/j.ijheh.2018.05.010.

Raczniak, G. A., Gaines, J., Bulkow, L. R., Kinzer, M. H., Hennessy, T. W., Klejka, J. A. & Bruce, M. G. 2016 A survey of knowledge, attitudes, and practices towards skin and soft tissue infections in rural Alaska. *International Journal of Circumpolar Health* **75** (1), 30603. https://doi.org/10.3402/ijch.v75.30603.

Ragin, C. C. 1987 *The Comparative Method: Moving Beyond Qualitative and Quantitative Strategies*. University of California, Oakland, CA.

Ragin, C. C. 2006 Set relations in social research: evaluating their consistency and coverage. *Political Analysis* **14** (3), 291–310. https://doi.org/10.1093/pan/mpj019.

Ragin, C. 2008a *User's Guide to Fuzzy-Set/Qualitative Comparative Analysis*.

Ragin, C. C. 2008b *The Comparative Method: Moving Beyond Qualitative and Quantitative Strategies* (1. Paperback Print., [Nachdr.]). University of California Press, Berkeley, CA.

Riggs, E., Hughes, J., Irvin, D. & Leopard, K. 2017 *An Overview of Clean Water Access Challenges in the United States* (Global Water Challenge, p. 32). University of North Carolina Environmental Finance Center, Chapel Hill, NC.

Rodgers, A. F., Ajono, L. A., Gyapong, J. O., Hagan, M. & Emerson, P. M. 2007 Characteristics of latrine promotion participants and non-participants; inspection of latrines; and perceptions of household latrines in Northern Ghana. *Tropical Medicine & International Health* **12** (6), 772–782. https://doi.org/10.1111/j.1365-3156.2007.01848.x.

Schneider, C. Q. & Wagemann, C. 2010 Standards of good practice in qualitative comparative analysis (QCA) and fuzzy-sets. *Comparative Sociology* **9** (3), 397–418. https://doi.org/10.1163/156913210X12493538729793.

Seymour, Z. & Hughes, J. 2014 Sanitation in developing countries: a systematic review of user preferences and motivations. *Journal of Water, Sanitation and Hygiene for Development* **4** (4), 681–691. http://dx.doi.org.colorado.idm.oclc.org/10.2166/washdev.2014.127.

Smiley, S. L. & Stoler, J. 2020 Socio-environmental confounders of safe water interventions. *WIREs Water* **7** (3). https://doi.org/10.1002/wat2.1438

Smith, D. W. & Low, N. 1996 *Cold Regions Utilities Monograph*, 3rd edn. American Society of Civil Engineers, New York, NY.

Starkl, M., Brunner, N. & Stenström, T.-A. 2013 Why do water and sanitation systems for the poor still fail? Policy analysis in economically advanced developing countries. *Environmental Science & Technology* **47** (12), 6102–6110. https://doi.org/10.1021/es3048416.

Thomas, T. K., Bell, J., Bruden, D., Hawley, M. & Brubaker, M. 2013 Washeteria closures, infectious disease and community health in rural Alaska: a review of clinical data in Kivalina, Alaska. *International Journal of Circumpolar Health* **72** (1), 21233. https://doi.org/10.3402/ijch.v72i0.21233.

Tilley, E., Strande, L., Lüthi, C., Mosler, H.-J., Udert, K. M., Gebauer, H. & Hering, J. G. 2014 Looking beyond technology: an integrated approach to water, sanitation and hygiene in low income countries. *Environmental Science & Technology* **48** (17), 9965–9970. https://doi.org/10.1021/es501645d.

US Environmental Protection Agency 2009 *National Primary Drinking Water Regulations*. US Environmental Protection Agency. Available from: https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations#one.

Yogananth, N. & Bhatnagar, T. 2018 Prevalence of open defecation among households with toilets and associated factors in rural south India: an analytical cross-sectional study. *Transactions of the Royal Society of Tropical Medicine and Hygiene* **112** (7), 349–360. https://doi.org/10.1093/trstmh/try064.

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